Analyzing and Optimizing Pumping Systems

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Glenn T. Cunningham, PhD, P.E.
Mechanical Engineering Department
Tennessee Tech University
gcunningham@tntech.edu

Five basic causes of less than optimal pumping system operation

- Installed *components* are inherently inefficient at the normal operating conditions
- The installed *components* have degraded in service
- More flow is being provided than the *system* requires
- More head is being provided than the *system* requires
- The equipment is being run when not required by the *system*

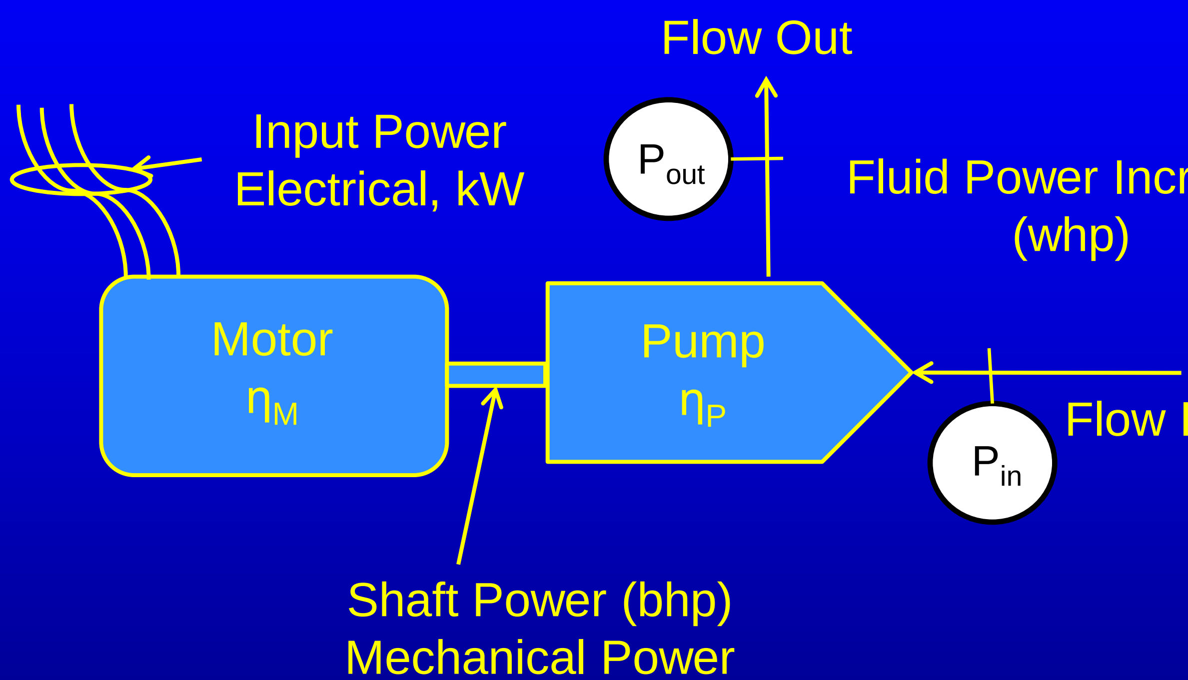
Continuing to narrow the field: symptoms in pumping systems that indicate potential opportunity

- Look for:
  - Throttle valve-controlled systems
  - Bypass (recirculation) line normally open
  - Multiple parallel pump system with same number of pumps always operating
  - Constant pump operation in a batch environment or frequent cycle batch operation in a continuous process
  - Cavitation noise (at pump or elsewhere in the system)
  - High system maintenance
  - Systems that have undergone change in function
  - Pump at higher flow rates than are necessary for shorter periods of time

Component and system approaches to energy and reliability improvement contrasted

- Component optimization involves segregating components and analyzing in isolation – How efficiently does the pump provide flow to the system?
- System optimization involves looking at how the whole group functions together and how changing one can help another – How efficient is the overall system at delivering the needed flow?

Pumping Power Diagram

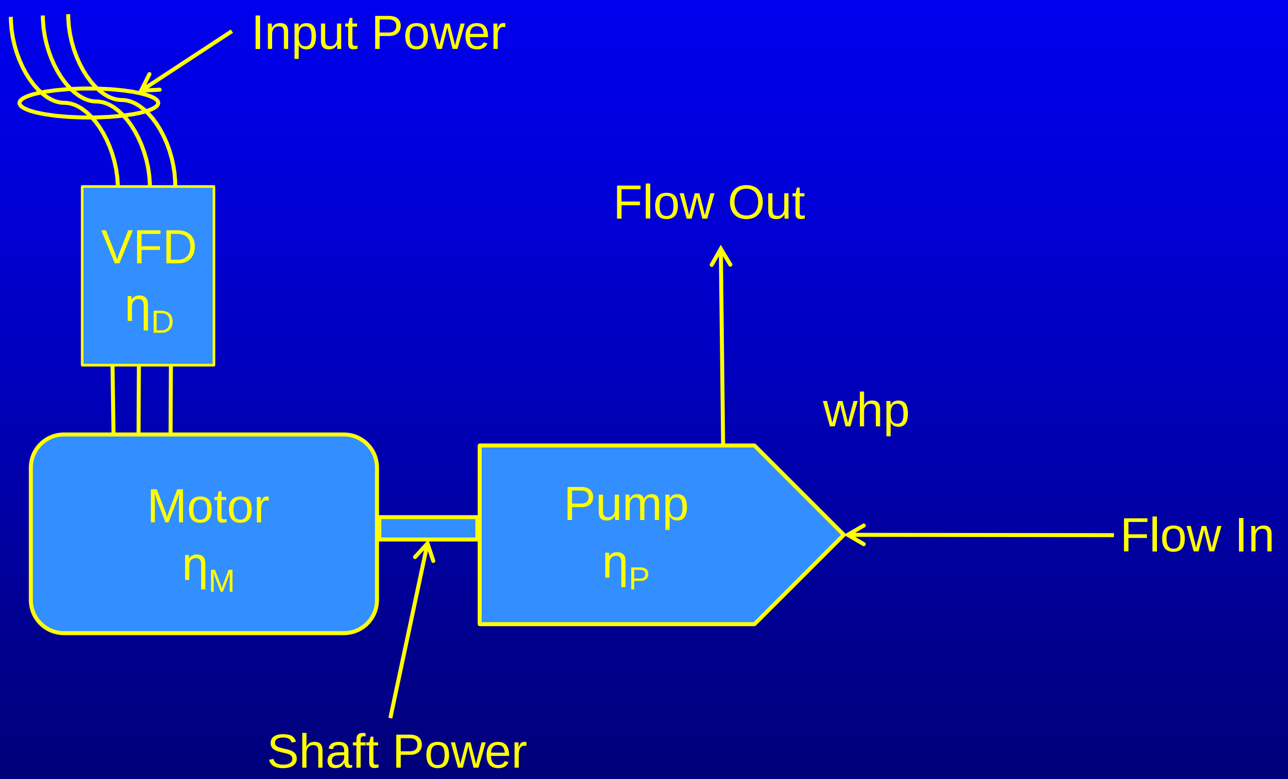


Shaft Power (bhp) = Motor Input Power * (η_M)

Fluid Energy Increase (whp) = Shaft Power (bhp) * (η_P)

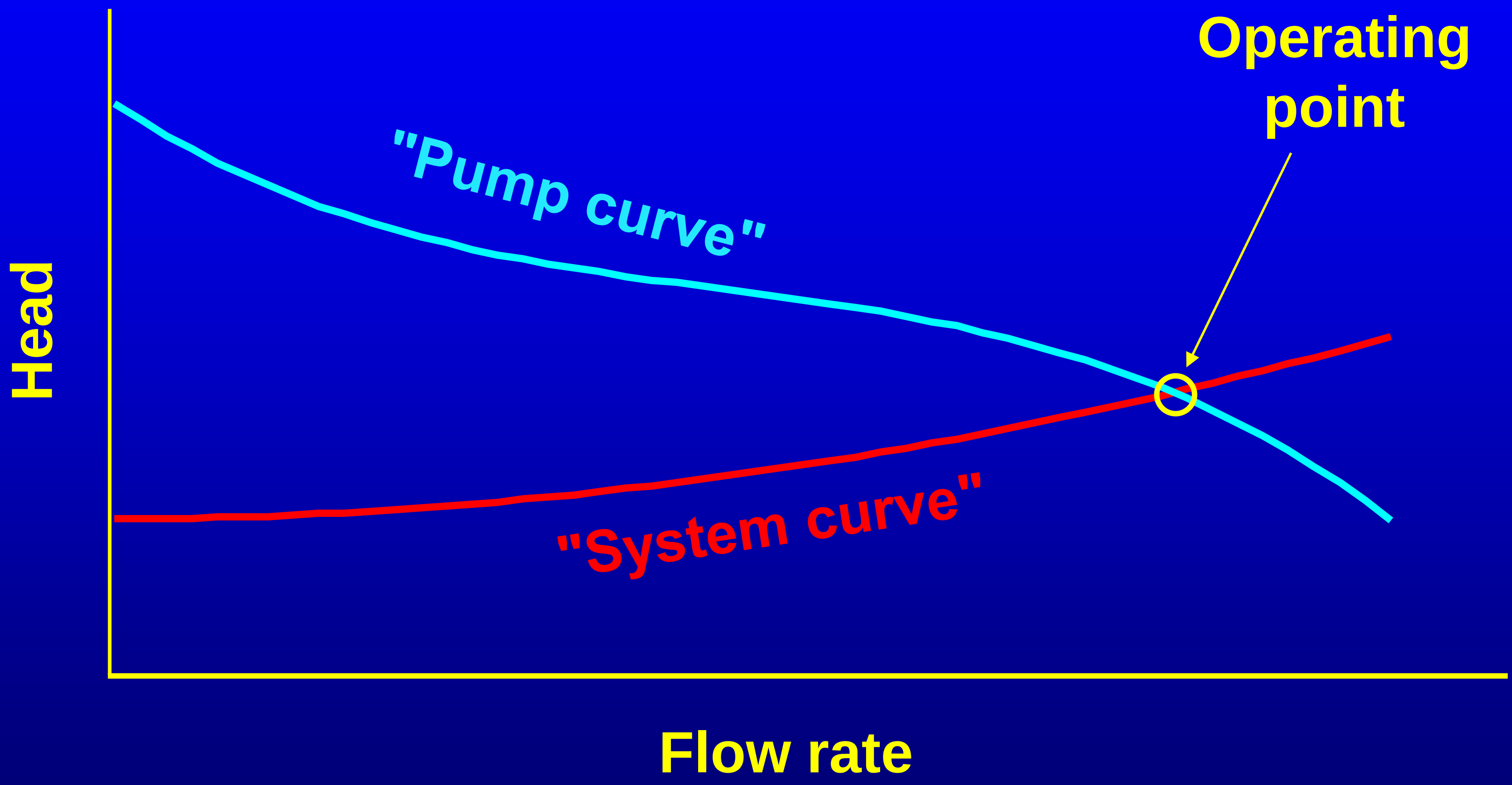
(1 HP = 0.746 kW)

VFD on Pump Motor



VFD Input Power = whp/(η_D * η_M * η_P)

The system operating point is at the intersection of the pump and system head-capacity curves

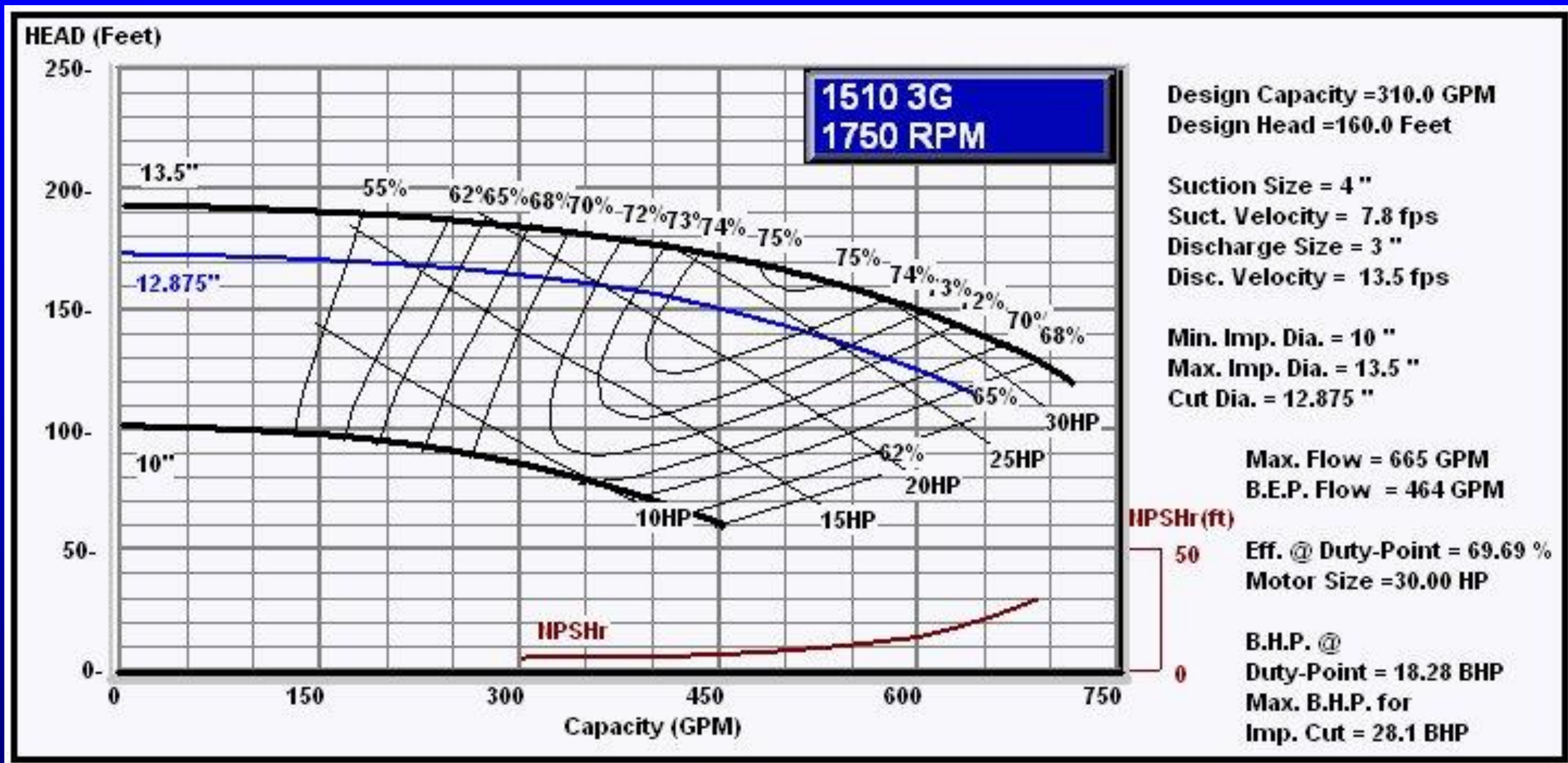


Pump performance characteristics

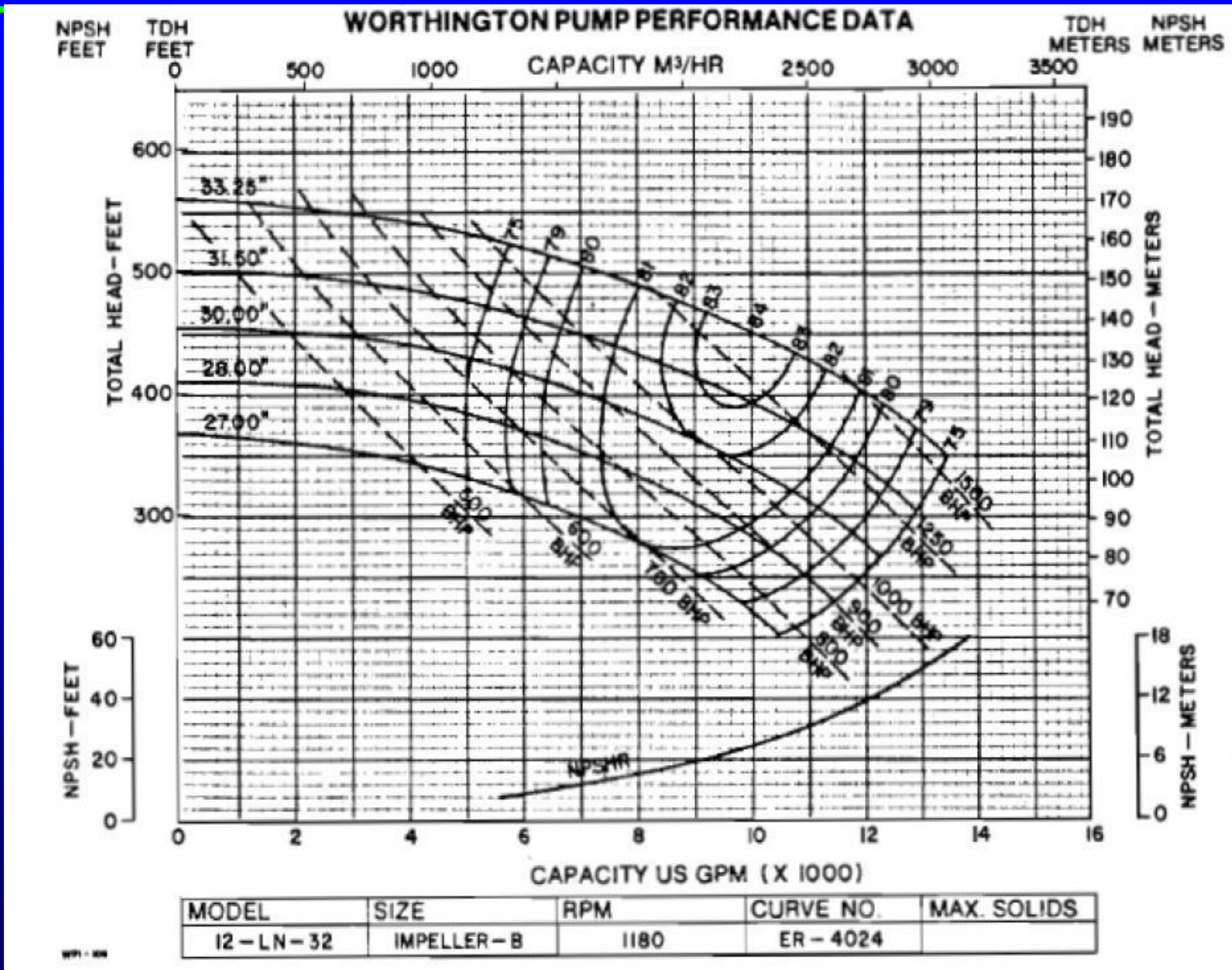
There are four types of performance curves that are used to characterize pumps

- Head
- Shaft power
- Efficiency
- Net positive suction head required (NPSHR)

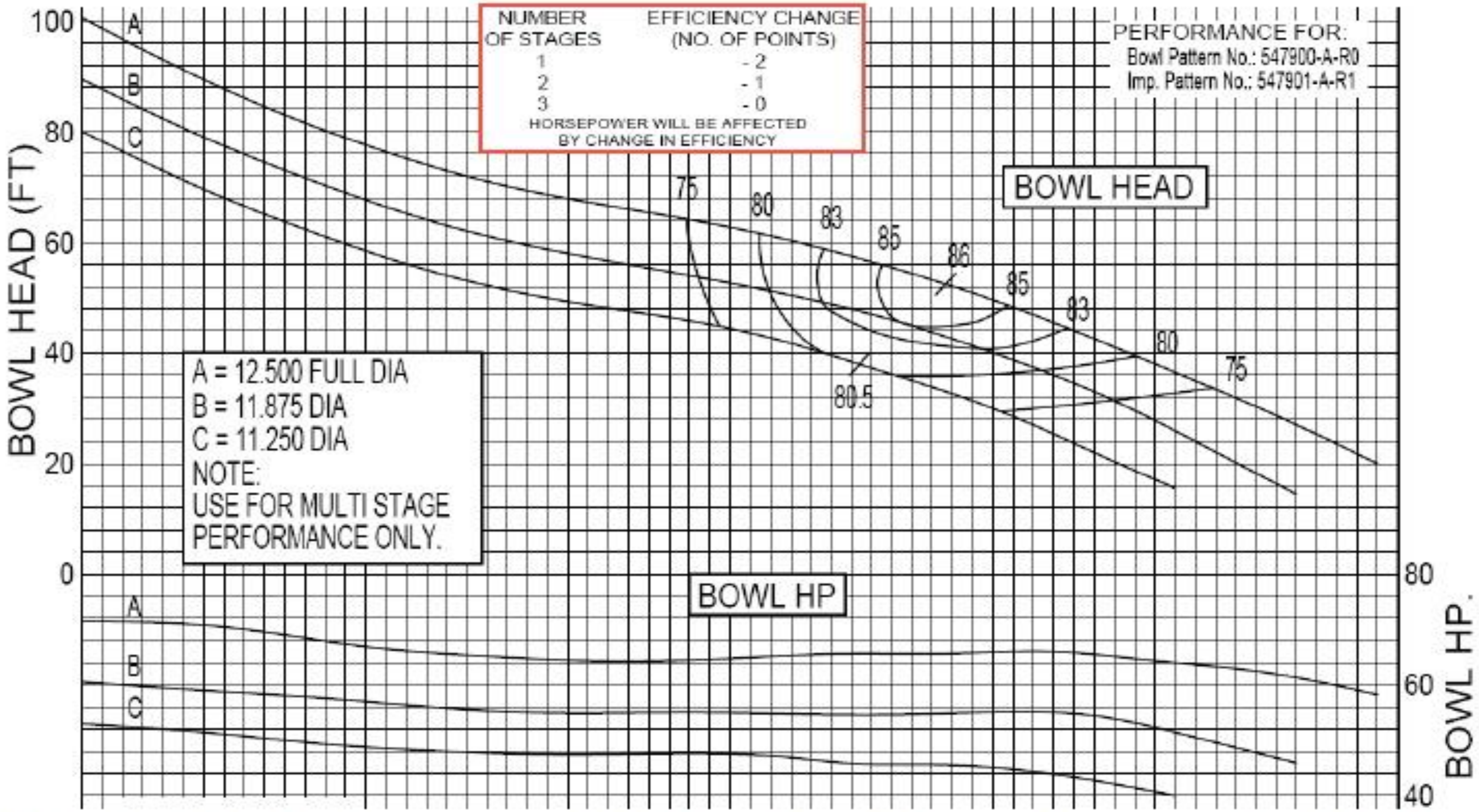
Actual Pump Curve



Actual Pump Curve

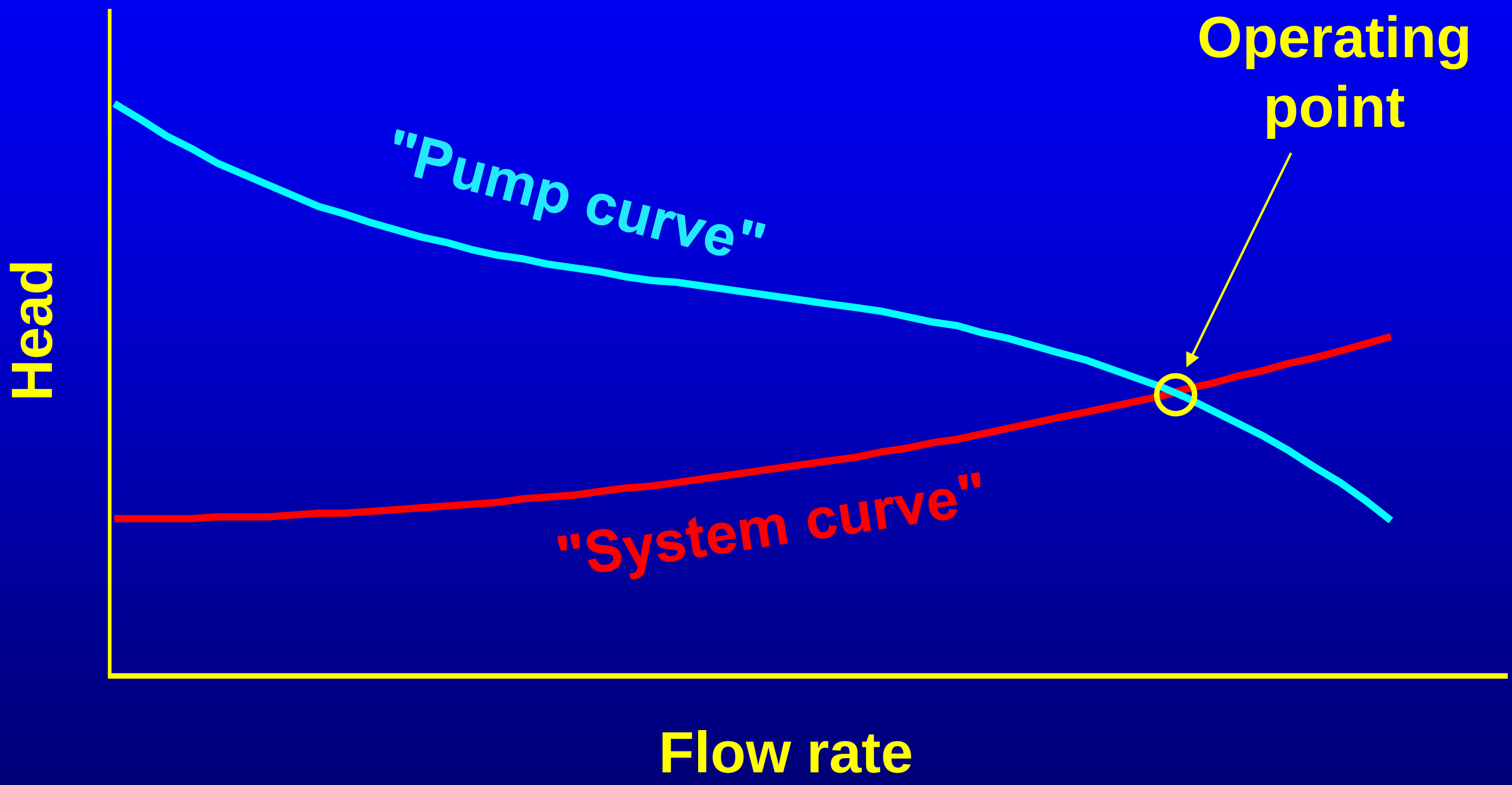


Vertical turbine pump catalog curves are commonly provided in individual stage (bowl) performance format



Note: Field performance will be affected by column, fitting losses

The system operating point is at the intersection of the pump and system head-capacity curves

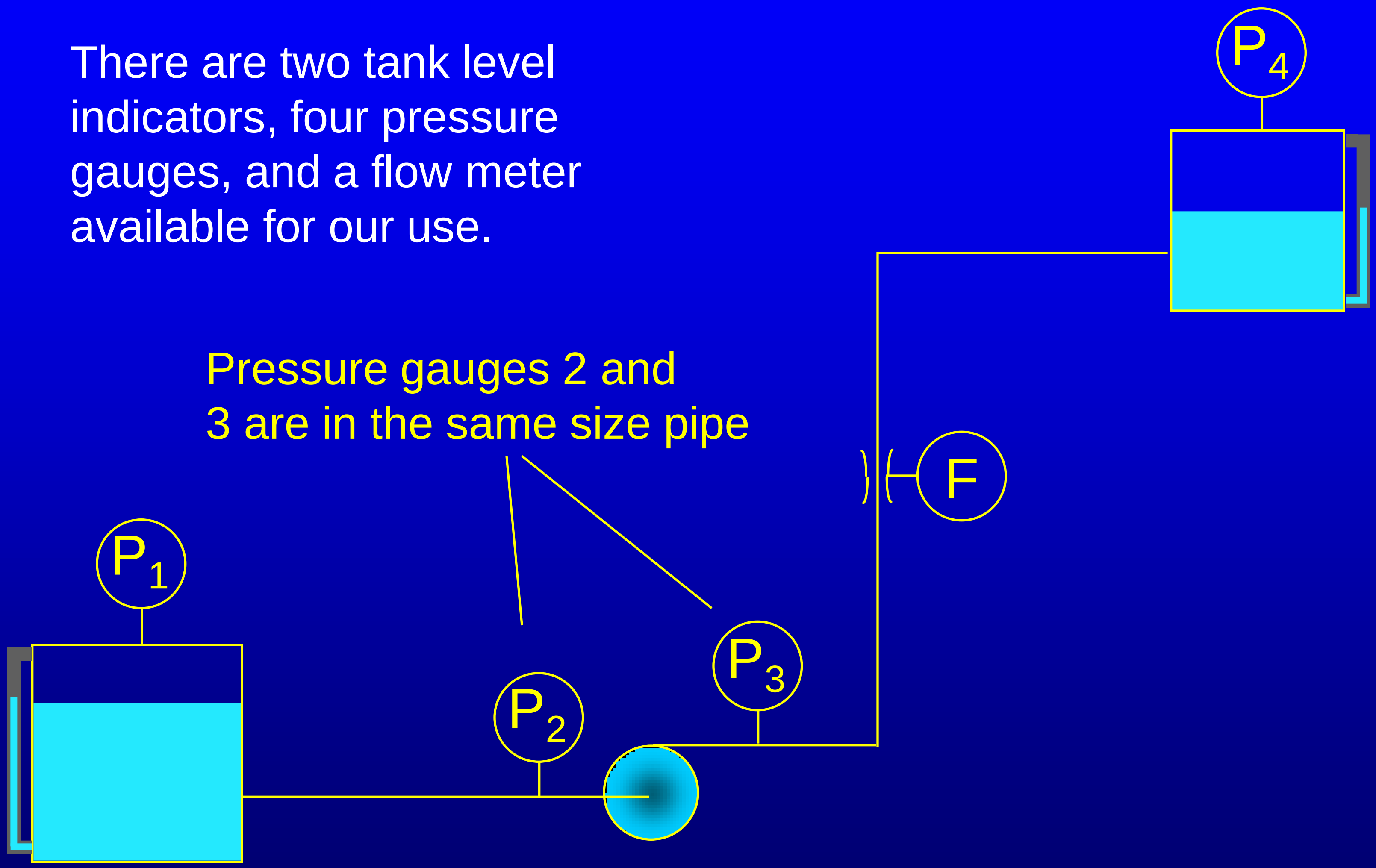


Each system has its own unique system curve

The system curve describes everything in the system except the pump and gives the required head to move a given flow rate through the system.

We'll use this system as an example: water is pumped from one tank to another

There are two tank level indicators, four pressure gauges, and a flow meter available for our use.



System curves are made up of two fundamental components - the static head and the frictional head

- Static head refers to the change in elevation from the suction tank to the discharge tank
- Tank over-pressures must be included in calculations
- This is basically the change in potential energy of fluid as it moves from the suction tank to the discharge tank
- Closed systems do not have static head
- Static heads can be positive, negative or zero

Two fundamental types of energy – or head – are required to move fluid through systems

- Static head: The head required to move a fluid from one elevation and pressure to another elevation and pressure
- Friction head: The head required to overcome the frictional losses in the pipe and fittings

$$H_{total} = H_{static} + H_{friction}$$

Static head is independent of flow rate, but friction head varies roughly proportional to the square of the flow rate

System Curves

System curves display the total head required to move different amounts of flow through the piping system

System curve equations:

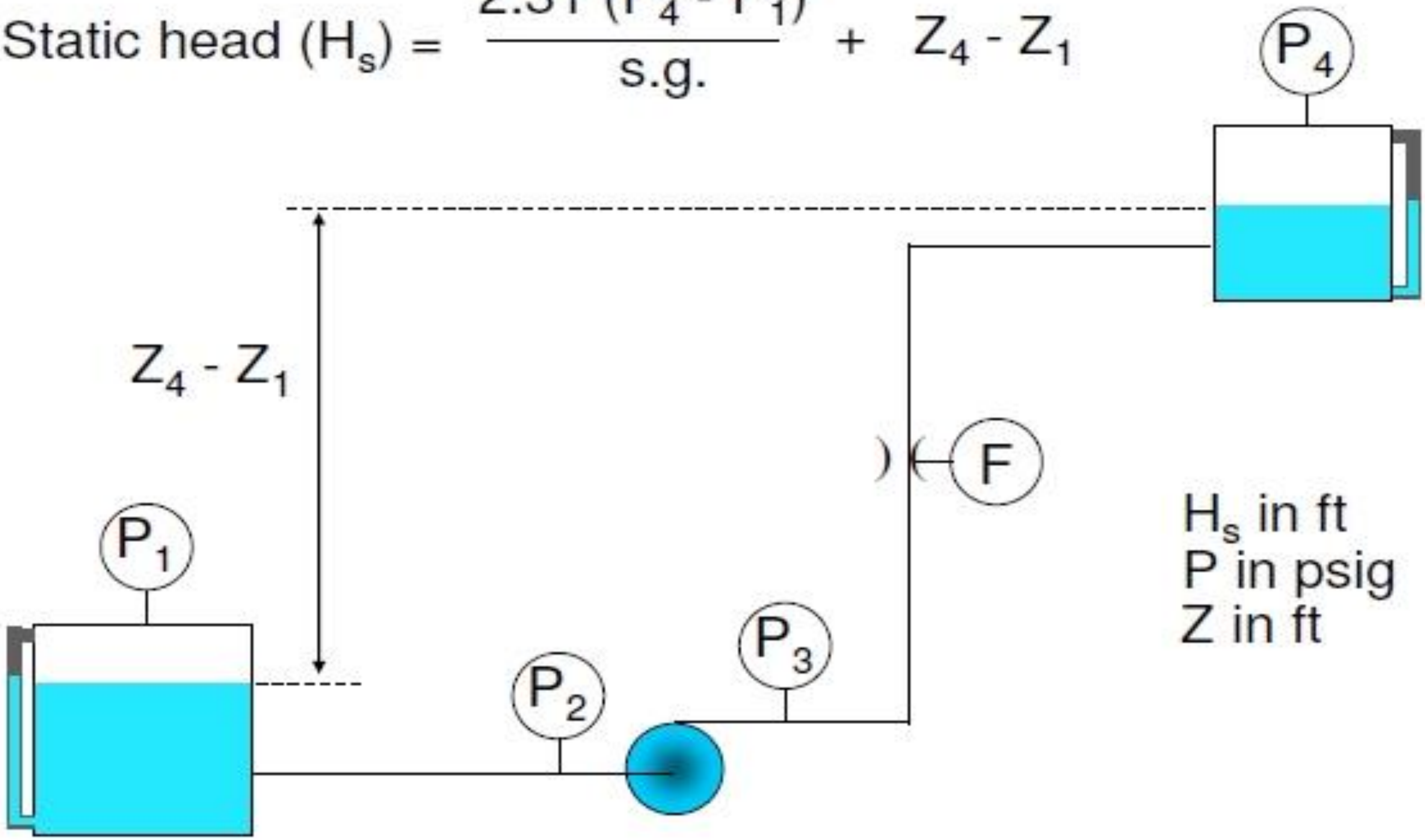
$$H_{total} = H_{static} + k'Q^{1.9}$$

Closed piping systems have zero static head

Open piping systems generally have some static head

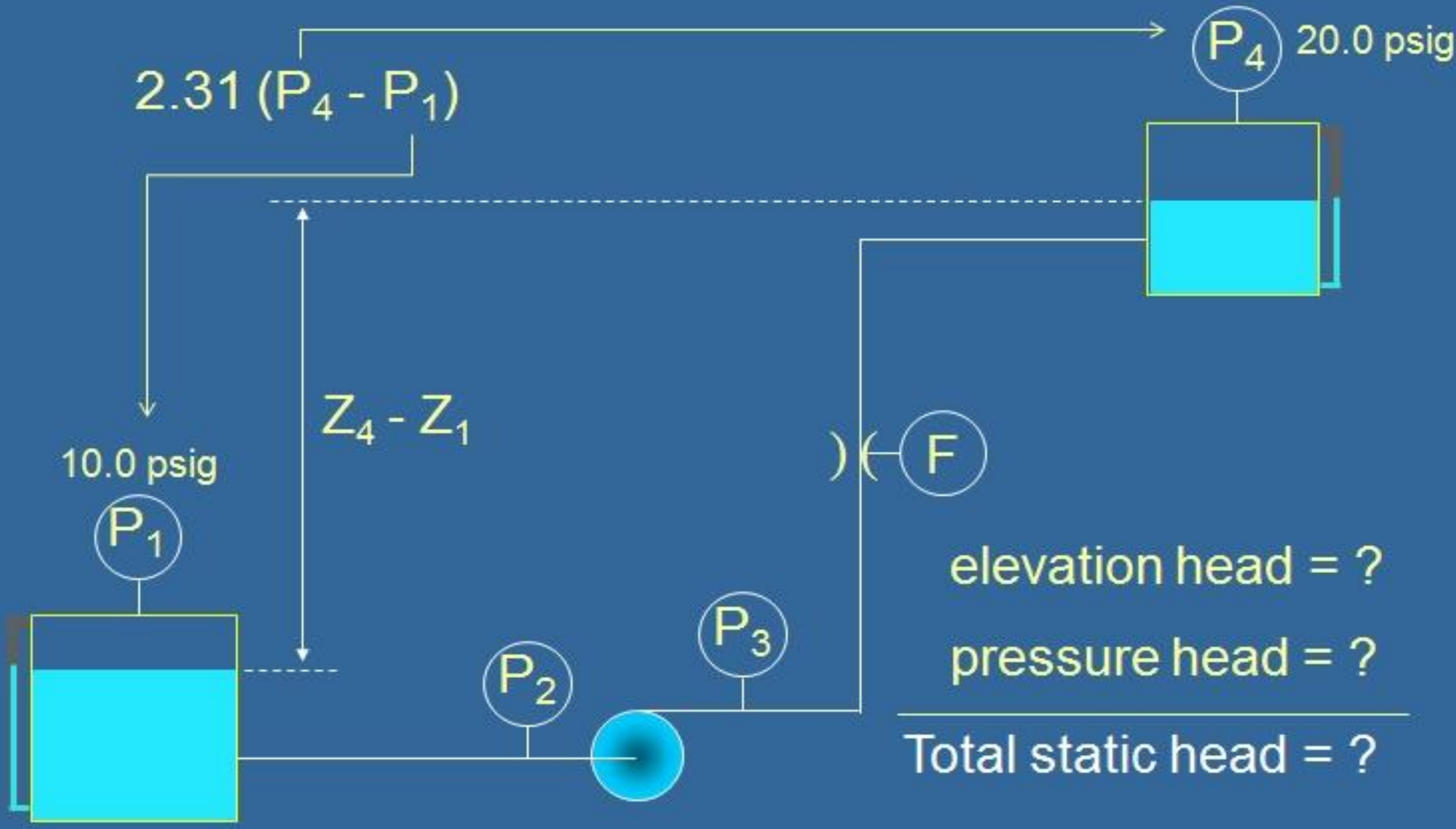
The static head is made up of elevation, and sometimes pressure components

$$\text{Static head } (H_s) = \frac{2.31\,(P_4 - P_1)}{\text{s.g.}} + Z_4 - Z_1$$



H_s in ft
P in psig
Z in ft

Example static head calculation

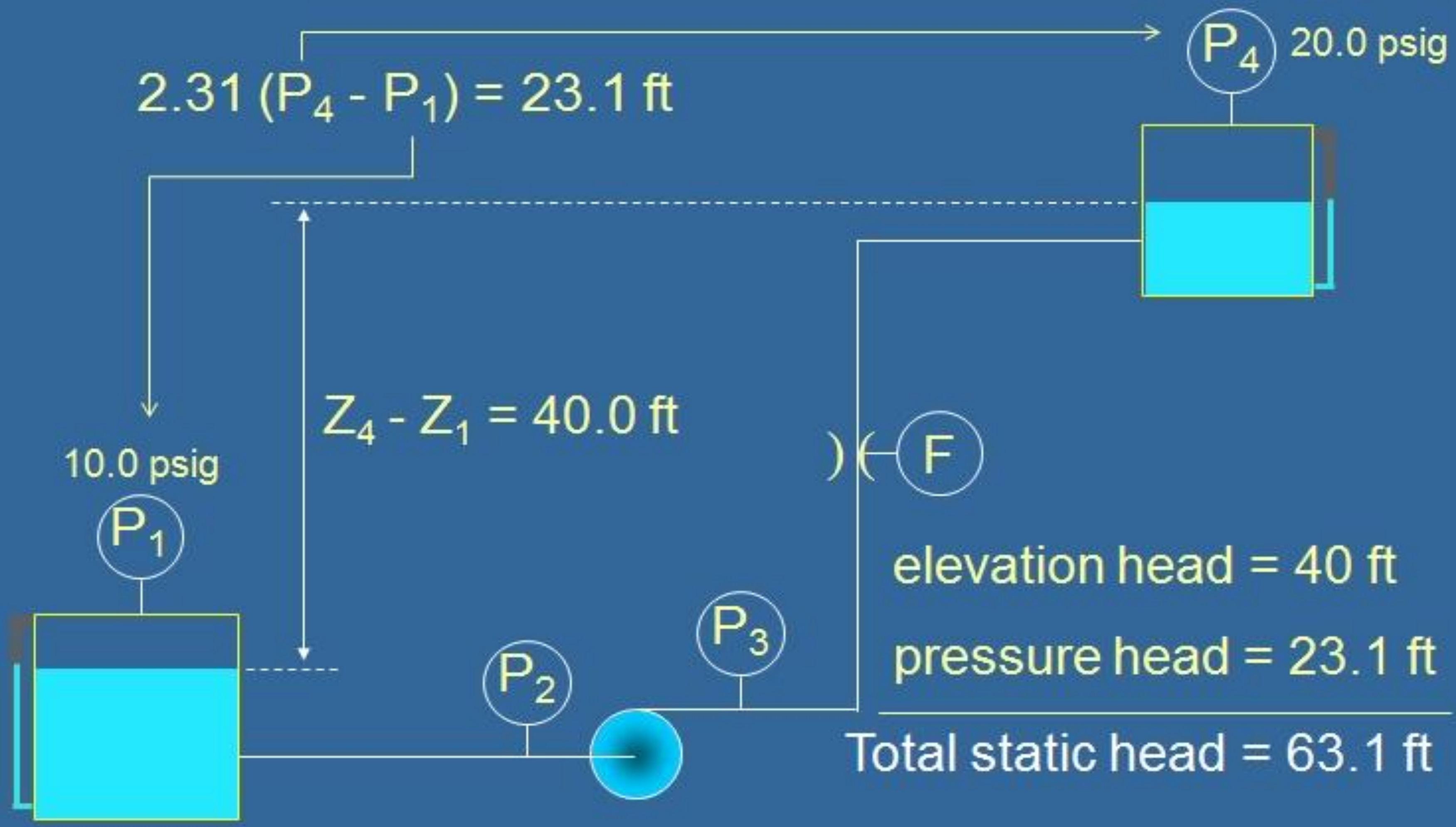


elevation head = ?

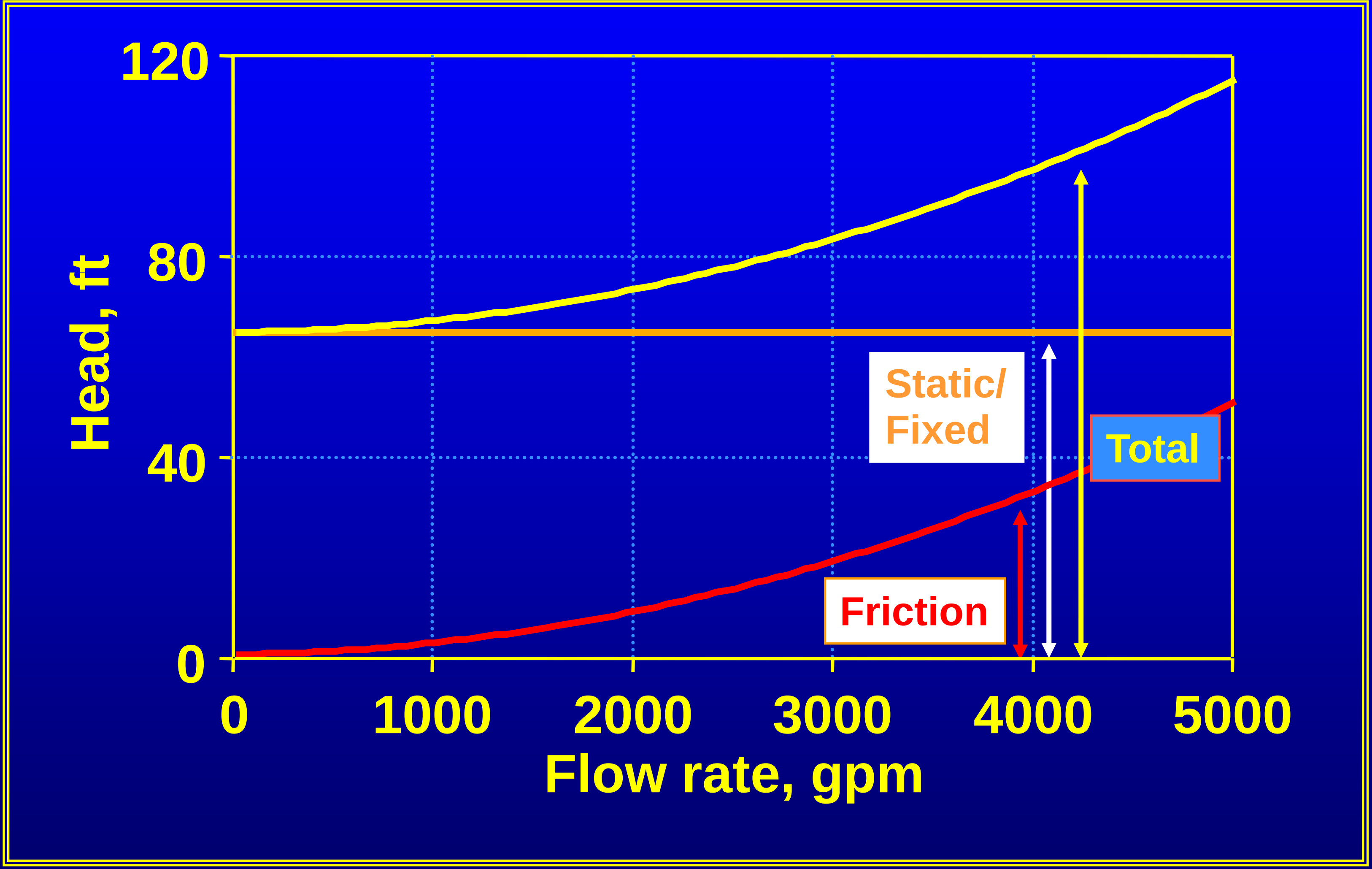
pressure head = ?

Total static head = ?

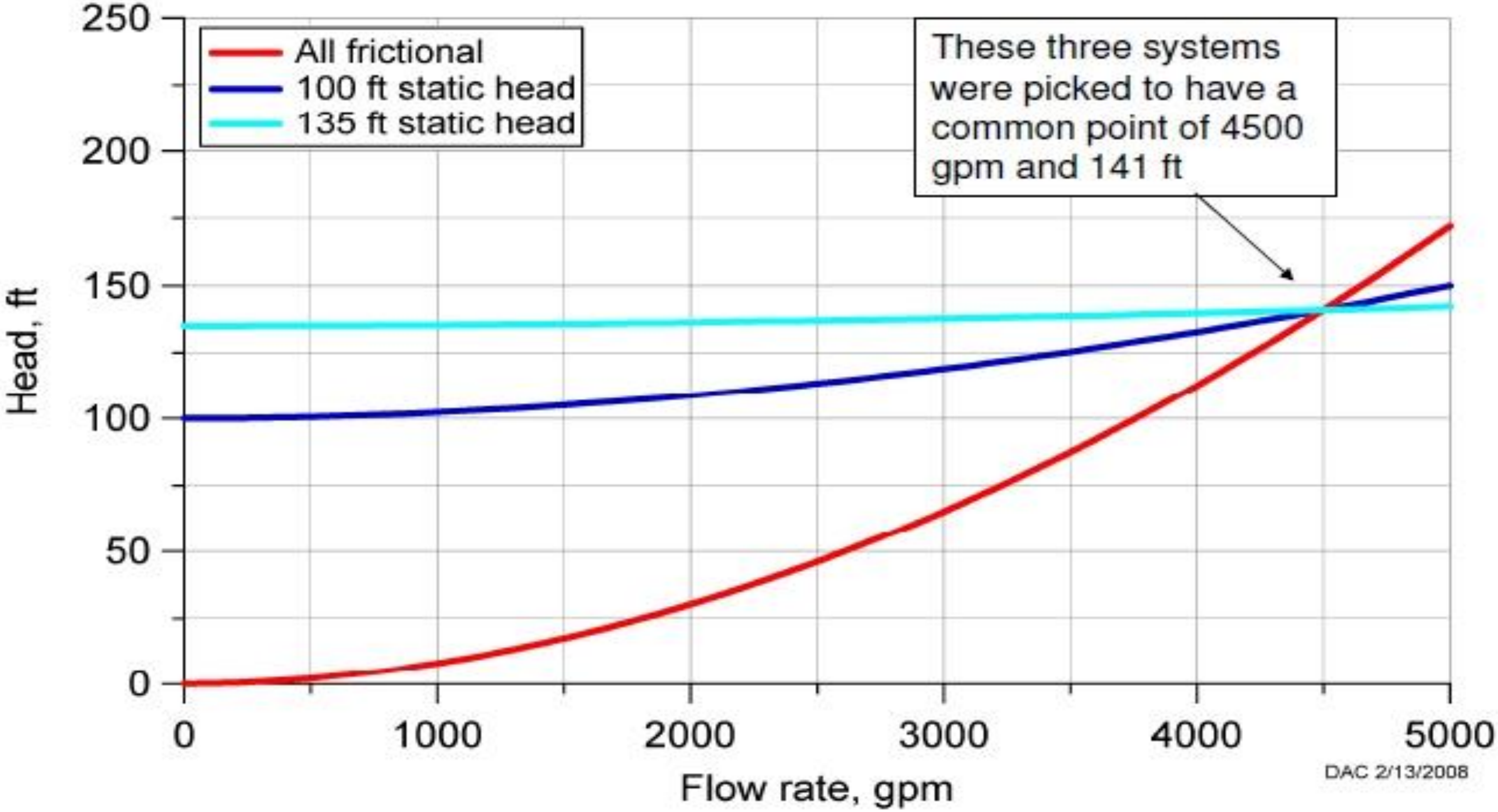
Example static head calculation



System curves are made up of two fundamental components - the static head and the frictional head

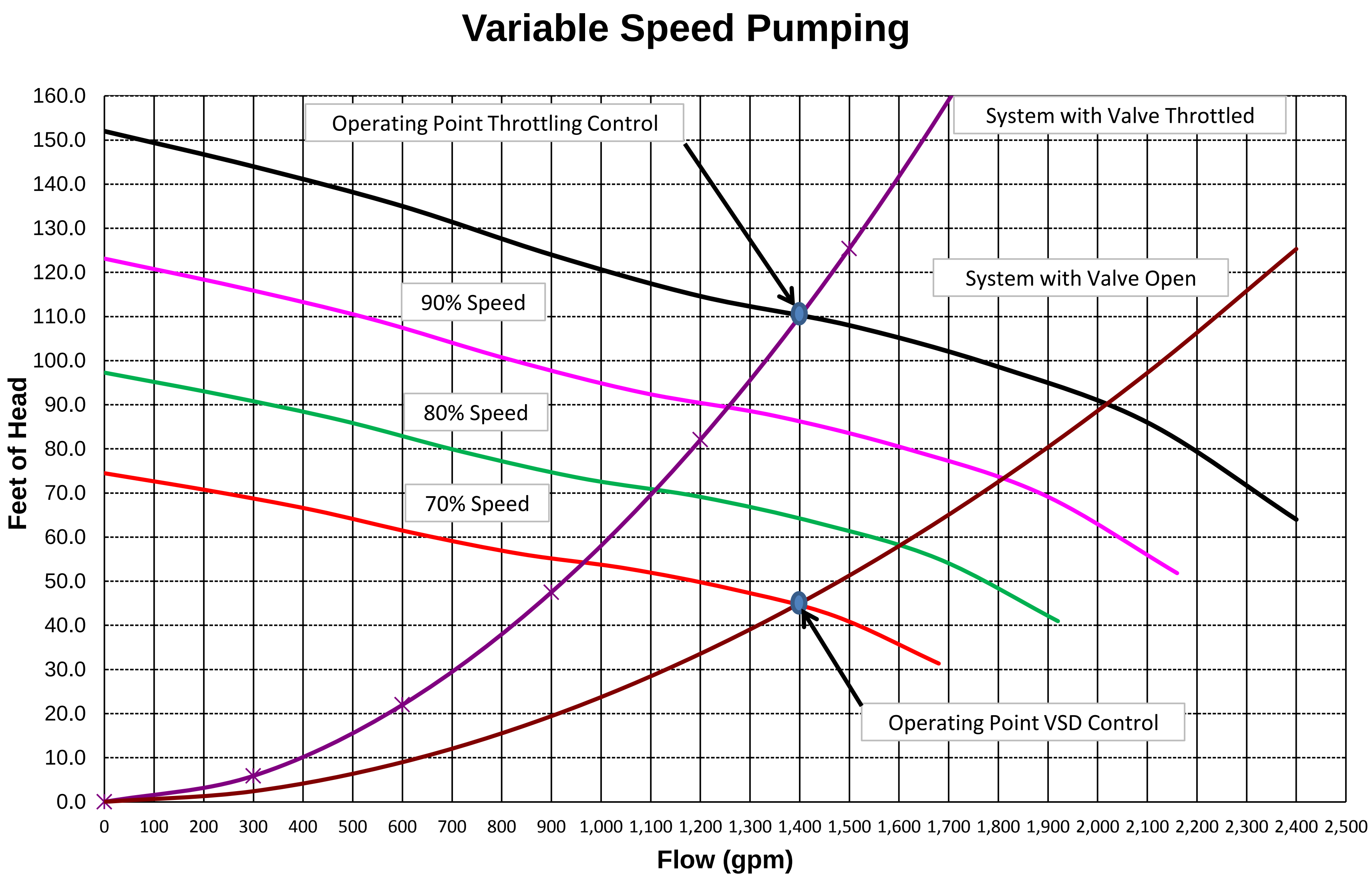


System head curves for three different systems



NOTE: These are three different systems

Actual Pump Data for VSD Operation



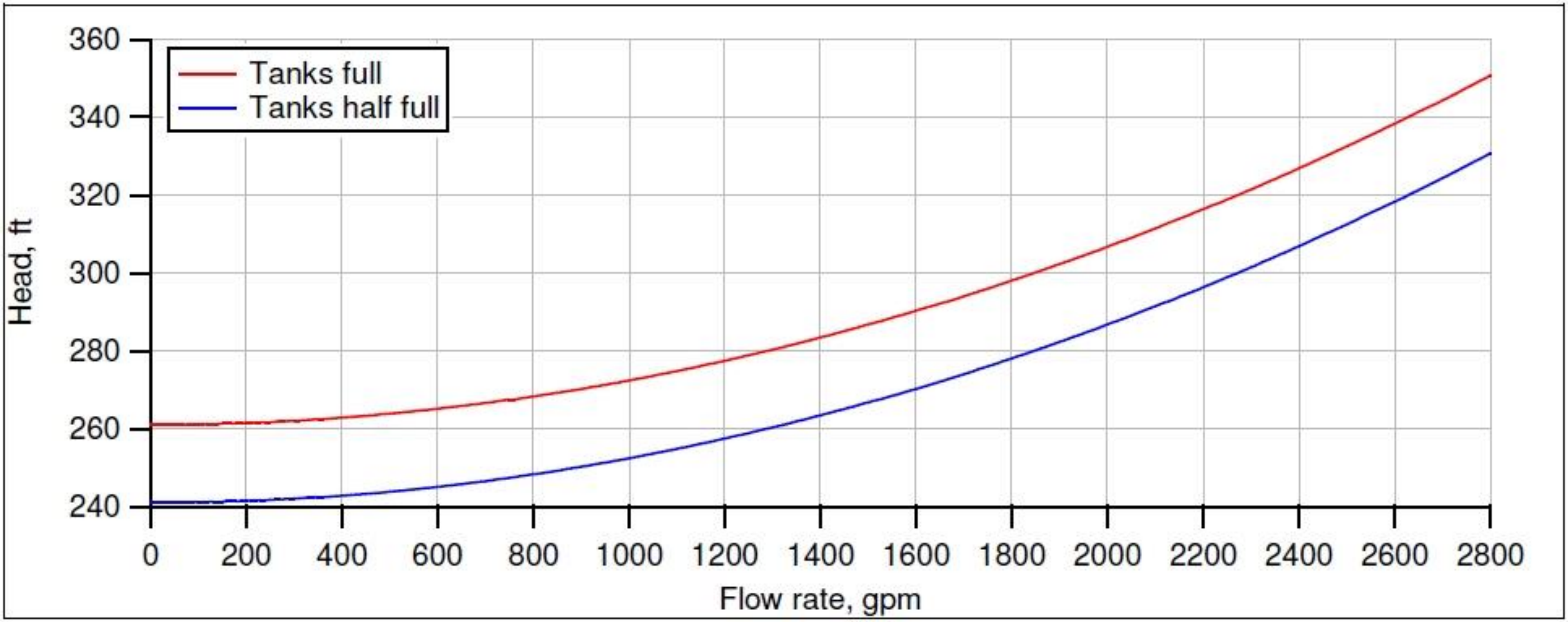
PSAT Introduction

Example Water Treatment Plant

- County water treatment facility
  - 200 HP pump
  - 2 100 HP pumps
  - Typically run the 200 HP and one 100 HP
- Peak demand is just under 1.6 MGD
- Demand is less than 1.5 MGD 99.5% of the time
- Would like to operate the plant 12 hours/day or less
- Electric rate has a significant demand charge

Example Water Treatment Plant

System Curves



City Water System

Pump gpm	ft	Required MGD	hrs/ day	operating fraction	PSAT kW optimal	Monthly unit costs: 1.2 MGD kwhr	Demand charge	Energy charge	Service fee	Tax	annual cost	avg. $/ kWhr
1700	294.1	1.2	11.76	0.490	113.6	40651	$628	$1,809	$9	$147	$31,106	0.0638
1800	298.1	1.2	11.11	0.463	121.6	41096	$707	$1,823	$9	$152	$32,293	0.0655
1900	302.3	1.2	10.53	0.439	129.8	41559	$788	$1,838	$9	$158	$33,512	0.0672
2000	306.8	1.2	10.00	0.417	138.5	42127	$873	$1,856	$9	$164	$34,837	0.0689
2100	311.4	1.2	9.52	0.397	147.4	42699	$961	$1,875	$9	$171	$36,189	0.0706
2200	316.4	1.2	9.09	0.379	156.4	43247	$1,050	$1,892	$9	$177	$37,543	0.0723
2300	321.5	1.2	8.70	0.362	165.9	43879	$1,144	$1,913	$9	$184	$38,995	0.0741
2400	326.9	1.2	8.33	0.347	175.8	44560	$1,242	$1,935	$9	$191	$40,517	0.0758
2500	332.5	1.2	8.00	0.333	185.8	45211	$1,340	$1,956	$9	$198	$42,039	0.0775

Pump gpm	ft	Required MGD	hrs/ day	operating fraction	PSAT kW optimal	Monthly unit costs: 1.5 MGD kwhr	Demand charge	Energy charge	Service fee	Tax	annual cost	avg. $/ kWhr
1700	294.1	1.5	14.71	0.613	113.6	50814	$628	$2,136	$9	$166	$35,270	0.0578
1800	298.1	1.5	13.89	0.579	121.6	51370	$707	$2,154	$9	$172	$36,502	0.0592
1900	302.3	1.5	13.16	0.548	129.8	51948	$788	$2,173	$9	$178	$37,769	0.0606
2000	306.8	1.5	12.50	0.521	138.5	52659	$873	$2,195	$9	$185	$39,152	0.0620
2100	311.4	1.5	11.90	0.496	147.4	53374	$961	$2,219	$9	$191	$40,562	0.0633
2200	316.4	1.5	11.36	0.473	156.4	54059	$1,050	$2,241	$9	$198	$41,973	0.0647
2300	321.5	1.5	10.87	0.453	165.9	54849	$1,144	$2,266	$9	$205	$43,489	0.0661
2400	326.9	1.5	10.42	0.434	175.8	55701	$1,242	$2,293	$9	$213	$45,081	0.0674
2500	332.5	1.5	10.00	0.417	185.8	56514	$1,340	$2,320	$9	$220	$46,670	0.0688

200-hp motor capable of handling loads through 2200 gpm (in service factor for 2200 gpm)

250-hp motor required for 2300 gpm and above

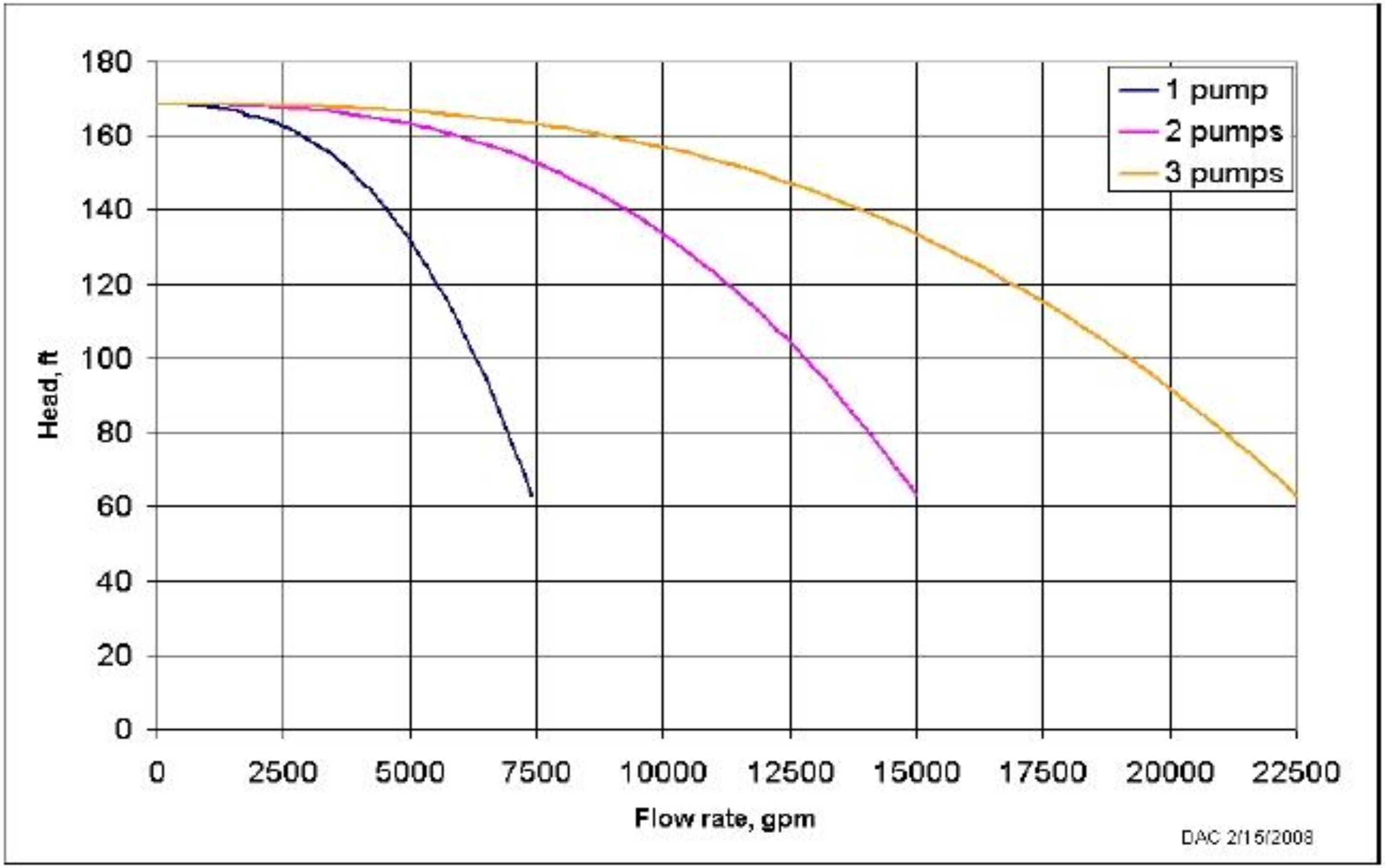
Figure 15. Spreadsheet showing optimal energy cost at various pump flow rates, based on average daily demands of 1.2 and 1.5 million gallons.

Energy charge:	First 15,000 kWhr each month @ 6.55 cents/kWhr, remainder @ 3.221 cents/kWhr
Demand charge:	$9.87 per kW for all demand above 50 kW, based on maximum 30-minute average during each month
Fixed service fee:	$9/month
Sales tax:	6% adder to sum of above charges

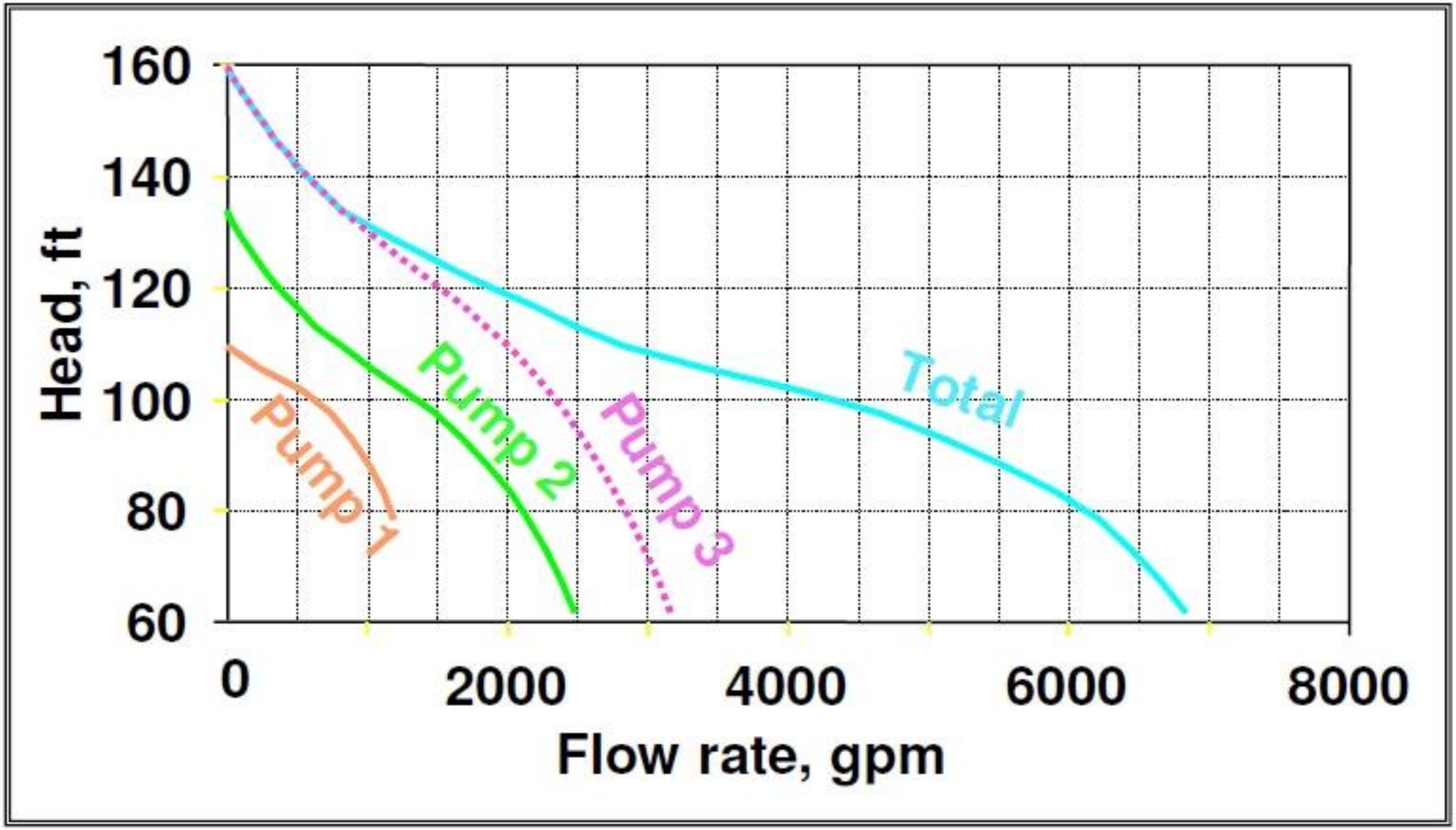
Parallel and series pumping “laws”, like the pump affinity laws apply to the pump curves *only*

- Parallel pumps - sum the flow rates at a given head
- Series pumps - sum the heads at a given flow rate

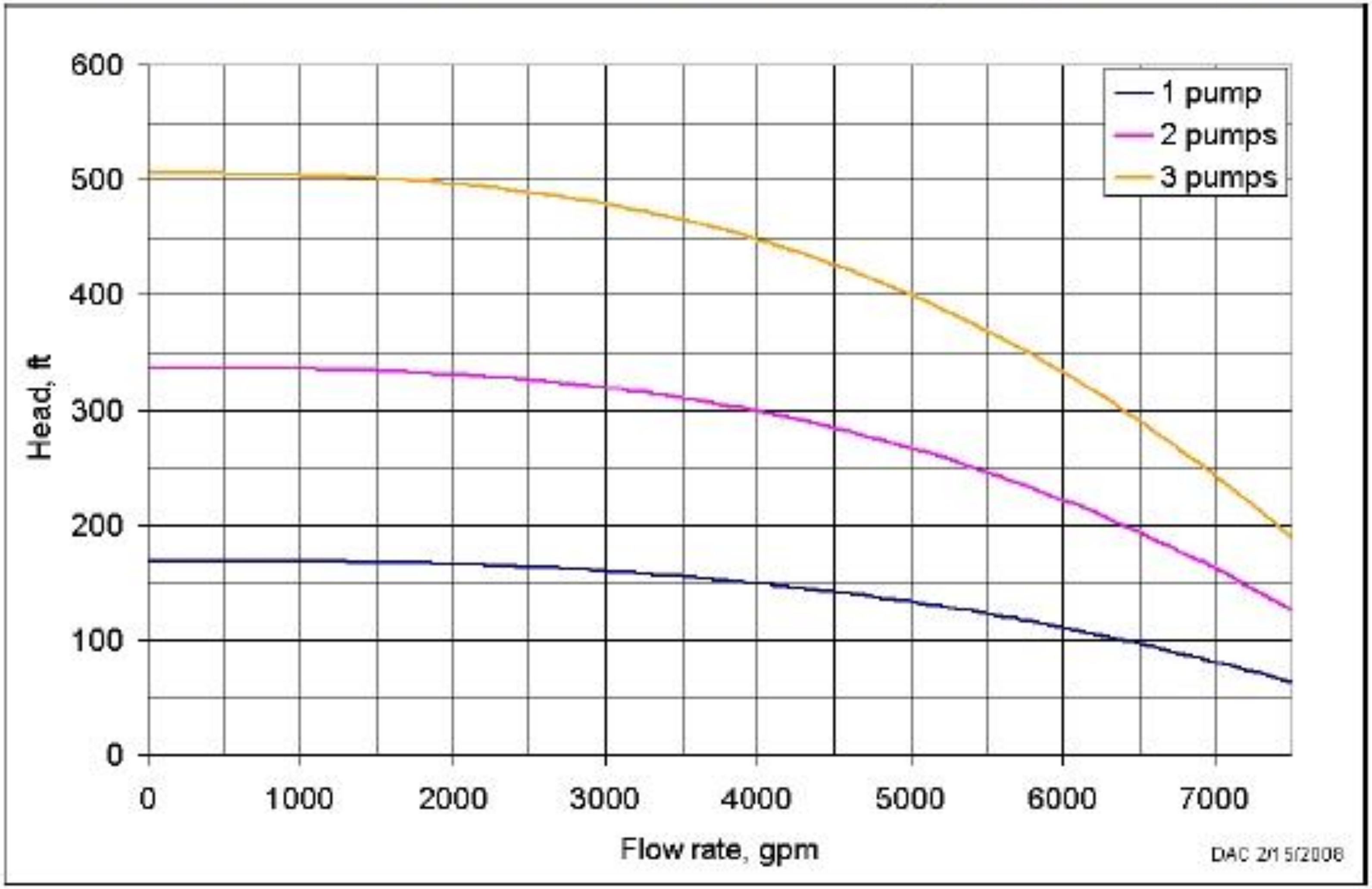
Parallel pumps can help adapt to changing system requirements and provide redundancy



Unlike pumps can also be used in parallel, <u>but with caution</u>



Identical pumps in series; add head at a given flow rate to estimate overall performance



Parallel Pumping Example

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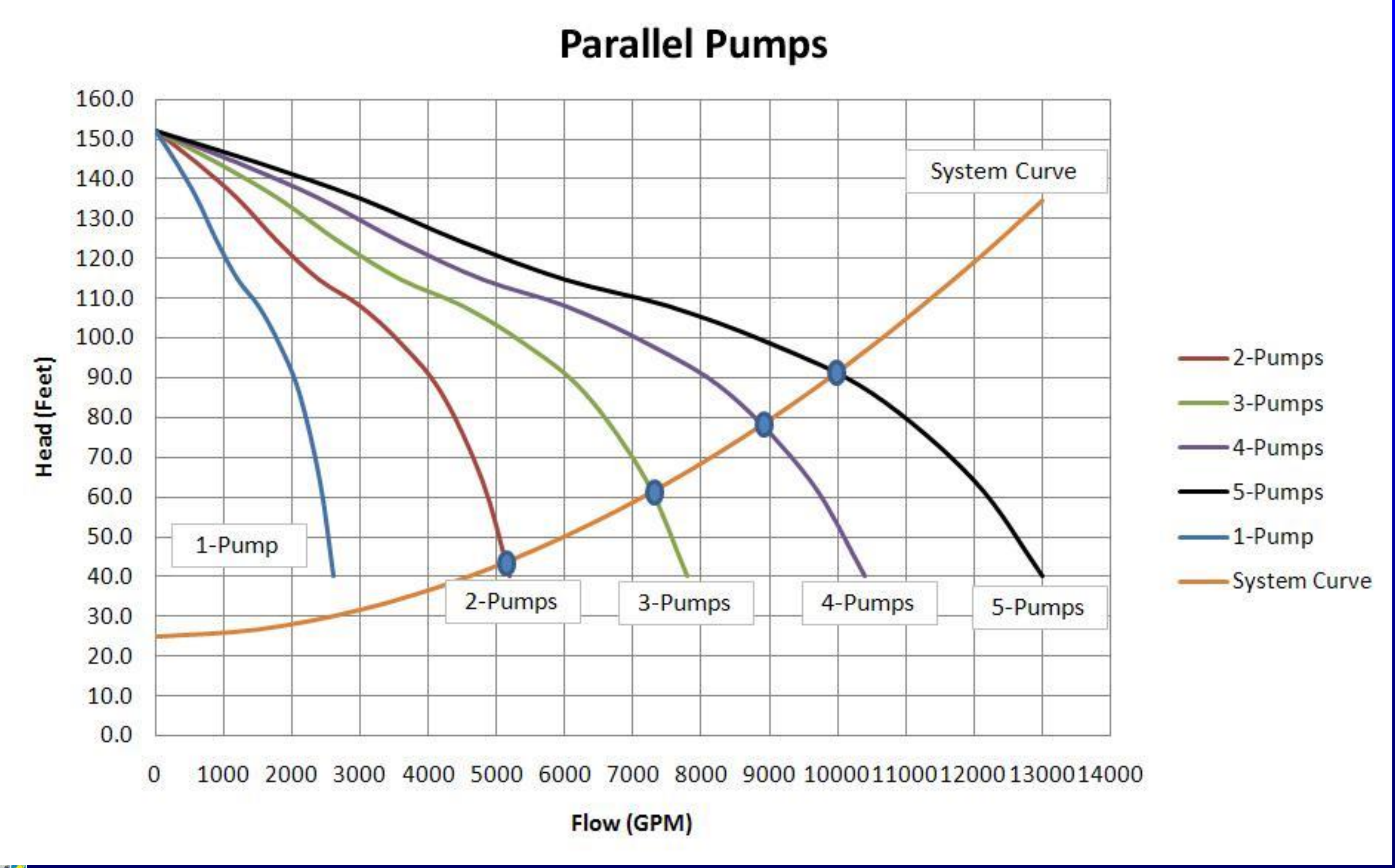
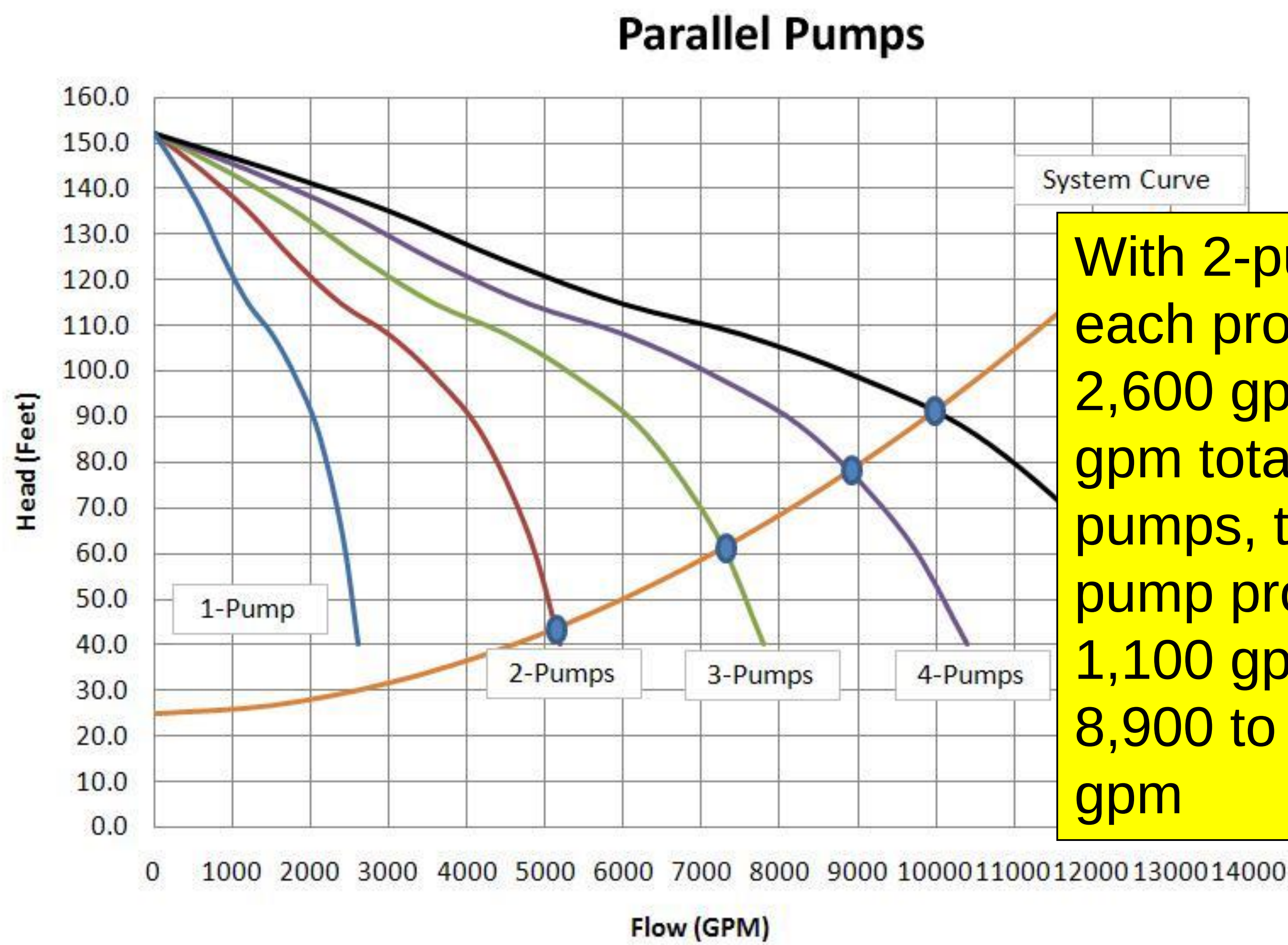
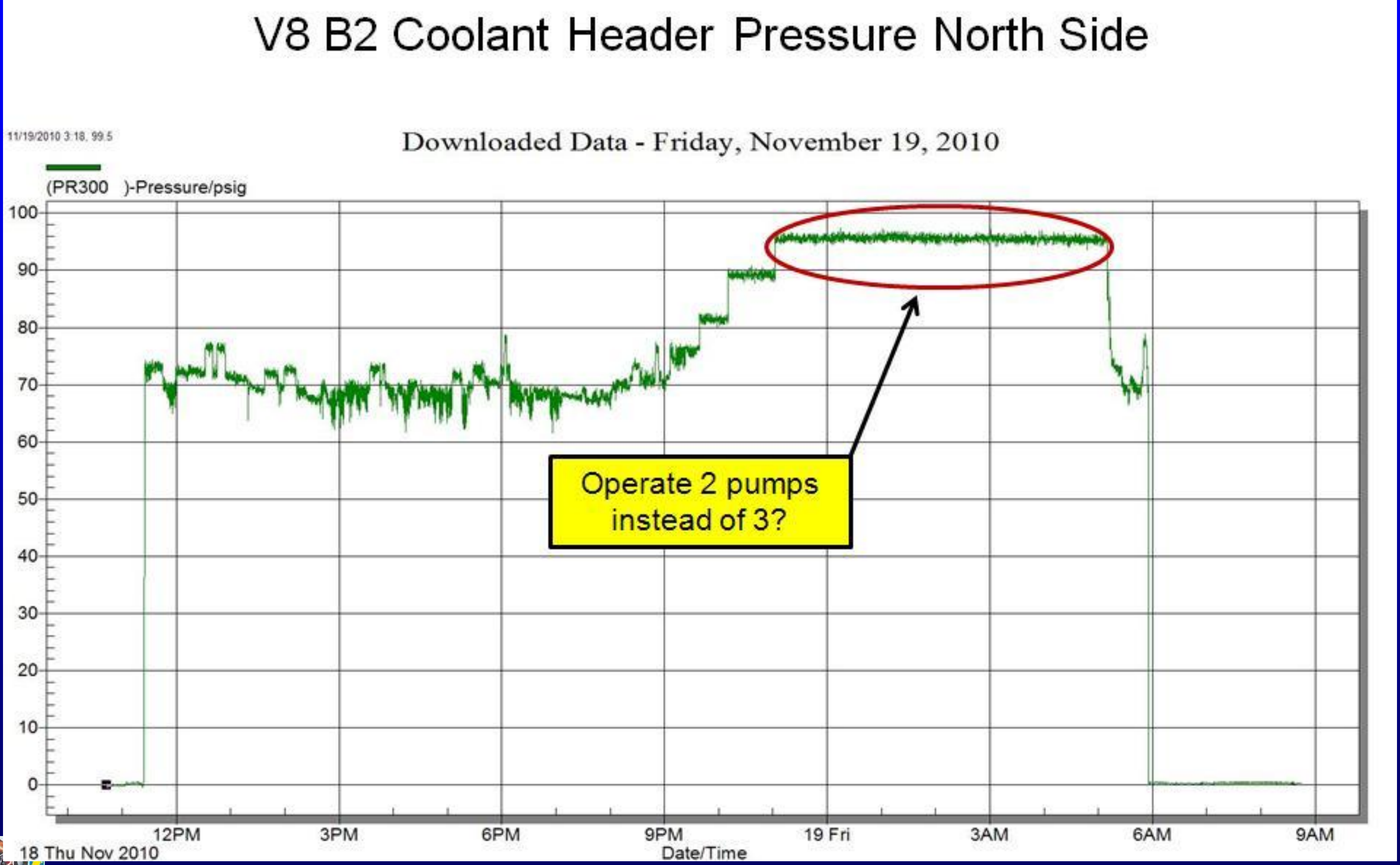


Parallel Pumping Example



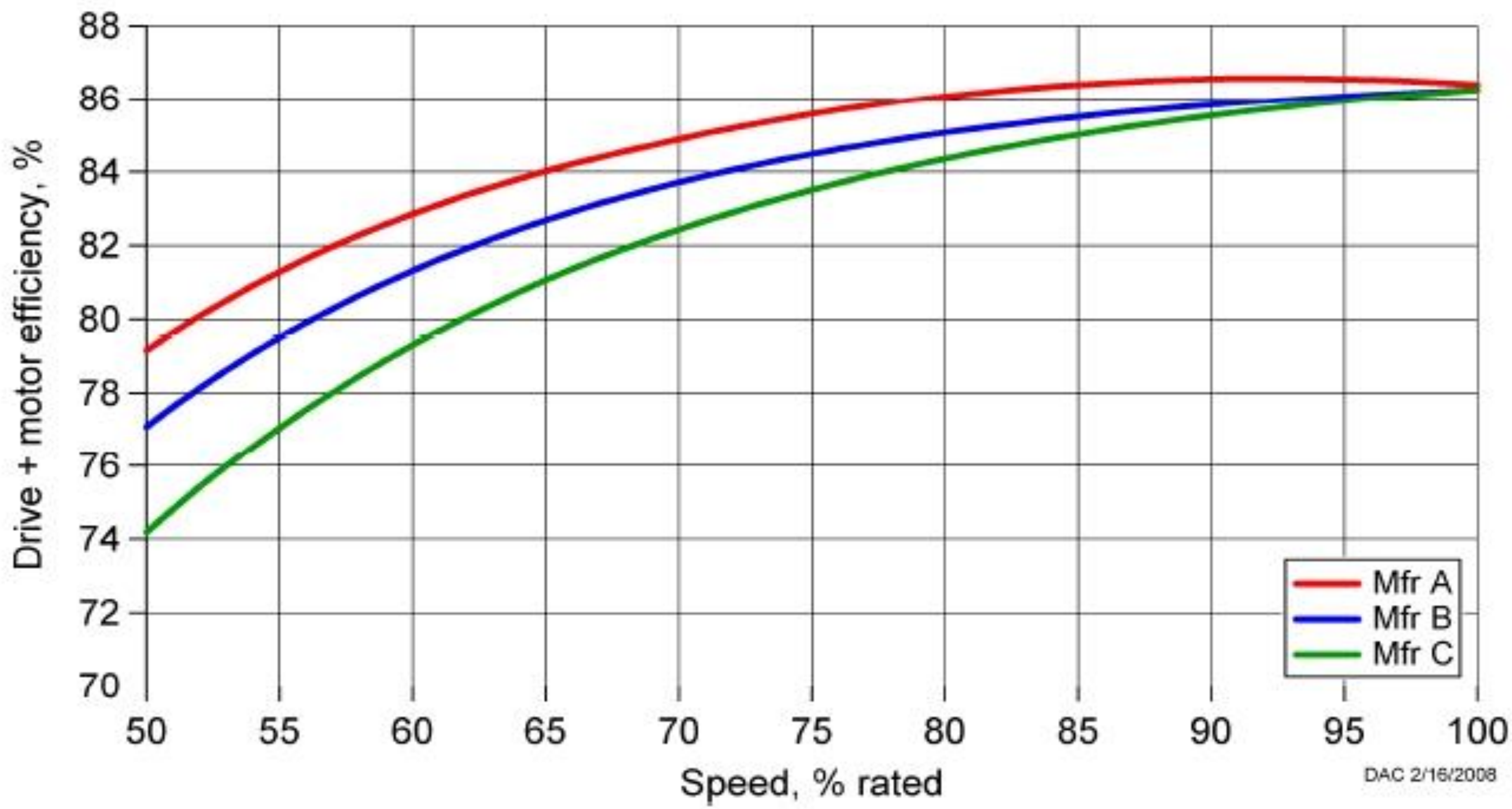
With 2-pumps, each produces 2,600 gpm, 5,200 gpm total; With 5-pumps, the last pump produces 1,100 gpm, from 8,900 to 10,000 gpm

Parallel Pumps: Header Pressure



Variable speed drive performance characteristics

Combined motor & adjustable frequency drive results demonstrate high drive efficiencies

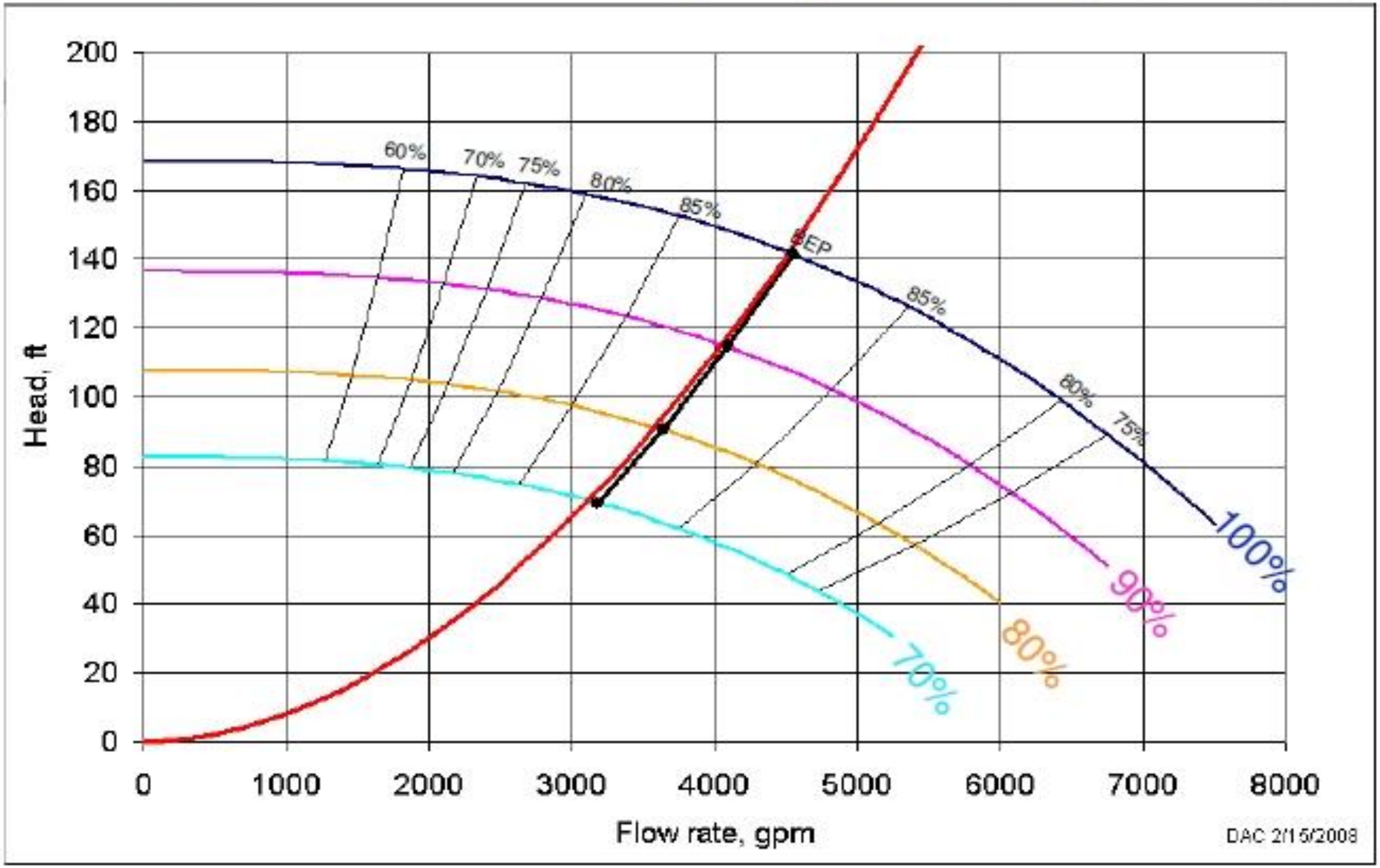


Note: 50-hp, 2-pole, standard efficiency motor (89% efficient @ full load)

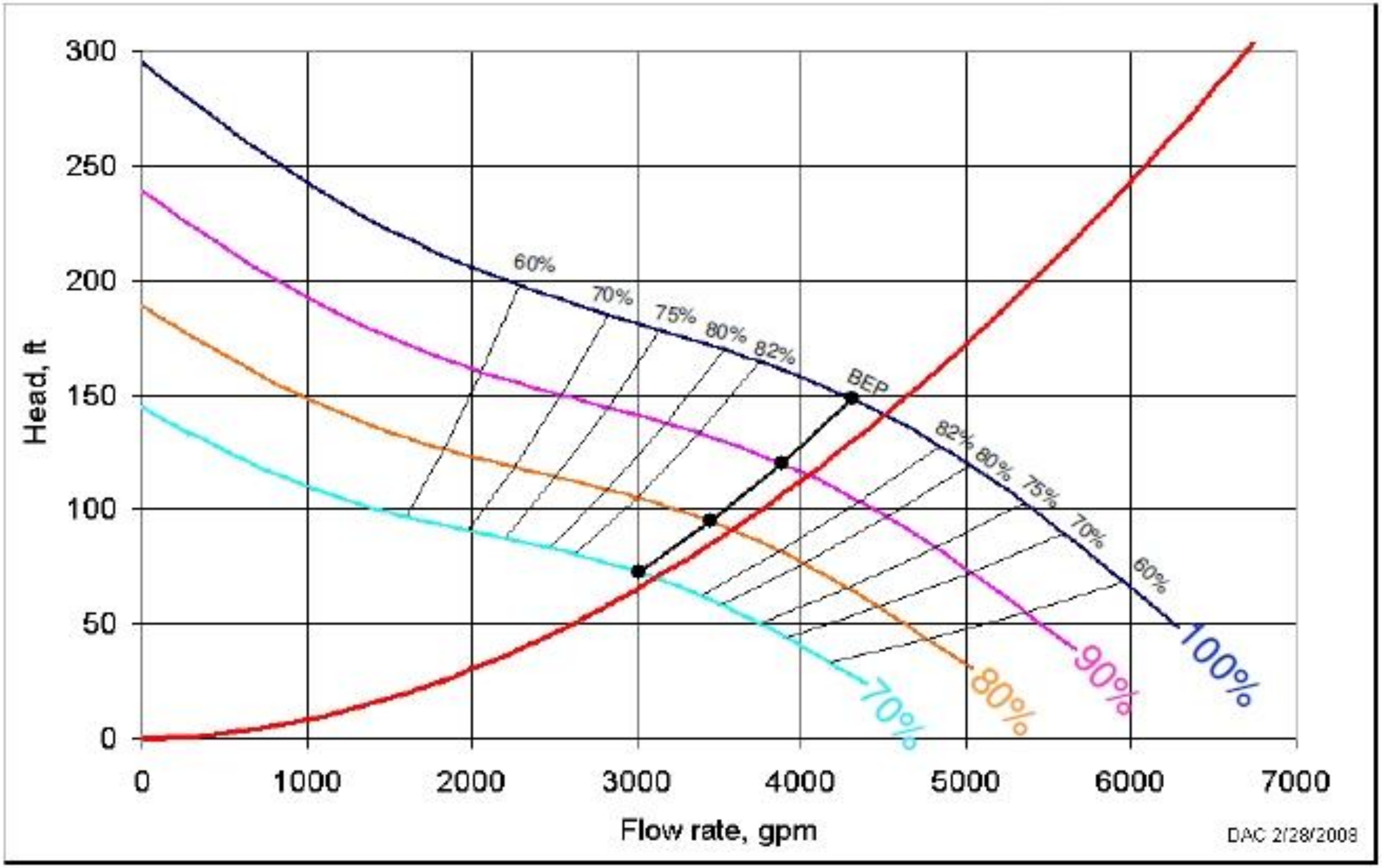
Source: Tests conducted at Y-12 plant motor test facility by Don Casada, Oak Ridge National Laboratory

What happens if we reduce pump speed in the three system types mentioned earlier?

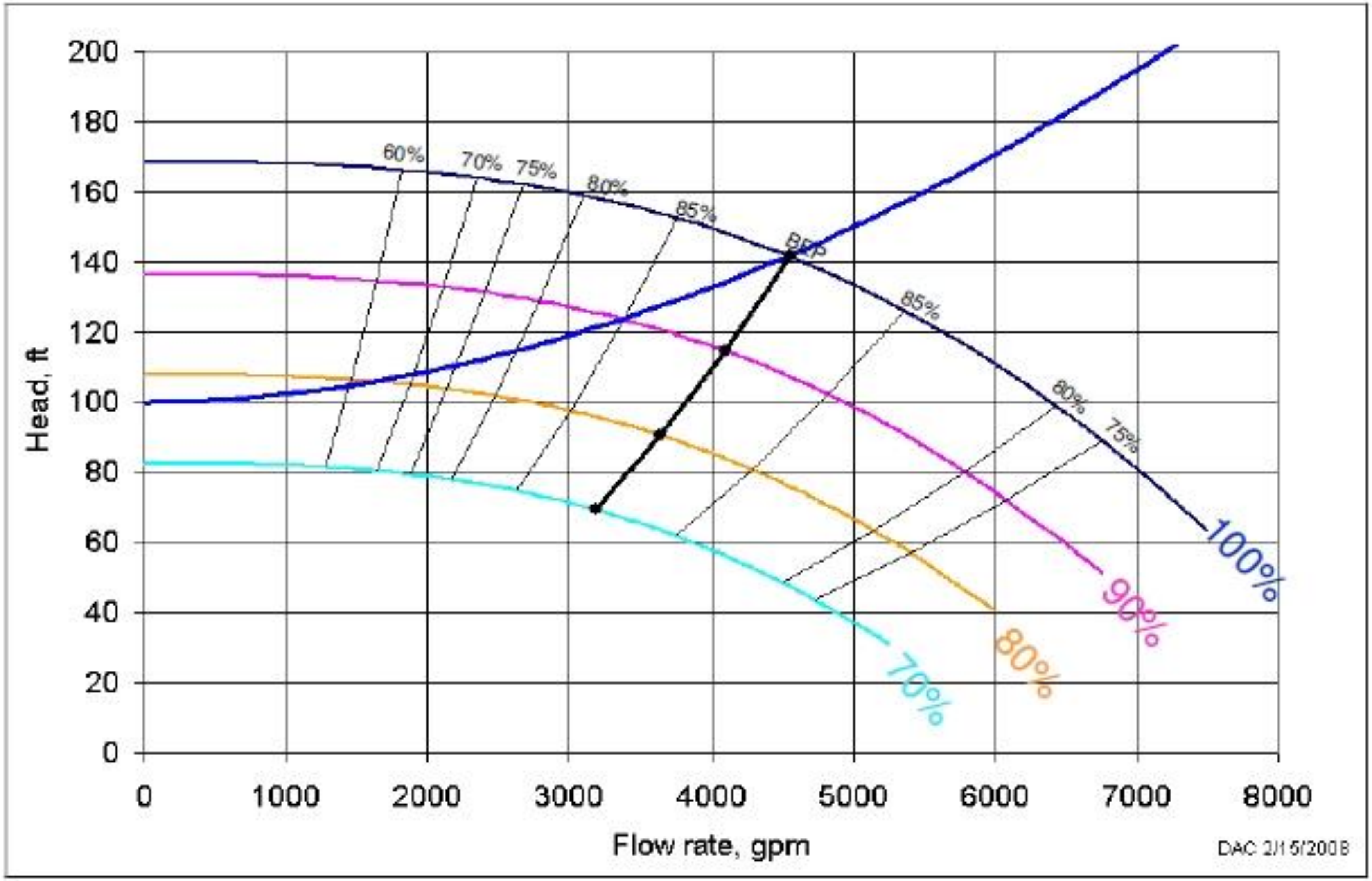
Change in speed for the all frictional system results in maintenance of constant pump efficiency (Pump 2)



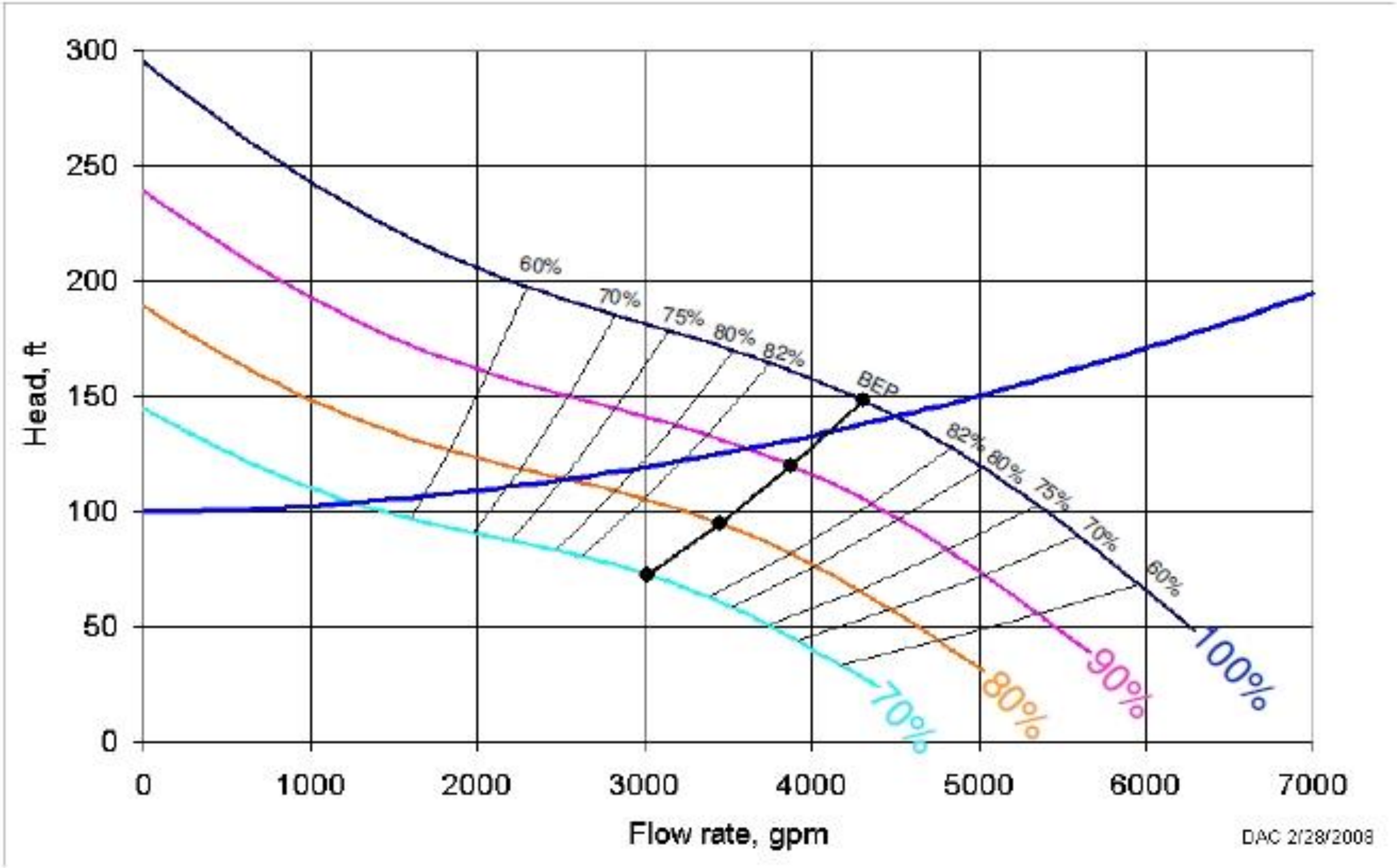
Change in speed for the all frictional system results in maintenance of constant pump efficiency (Pump 3)



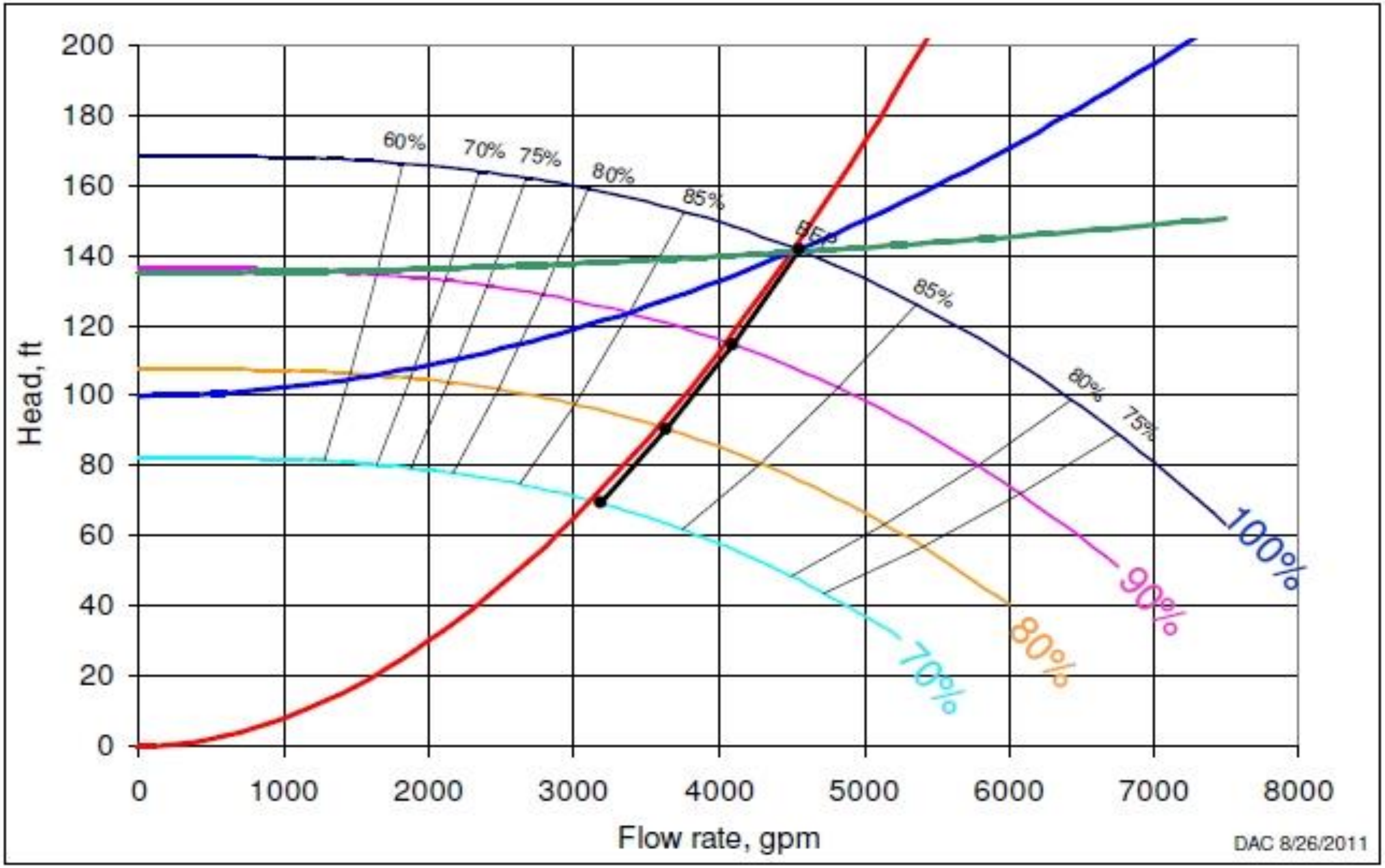
Change in speed for the 100-ft static system with Pump 2 results in loss of flow at ~78% speed



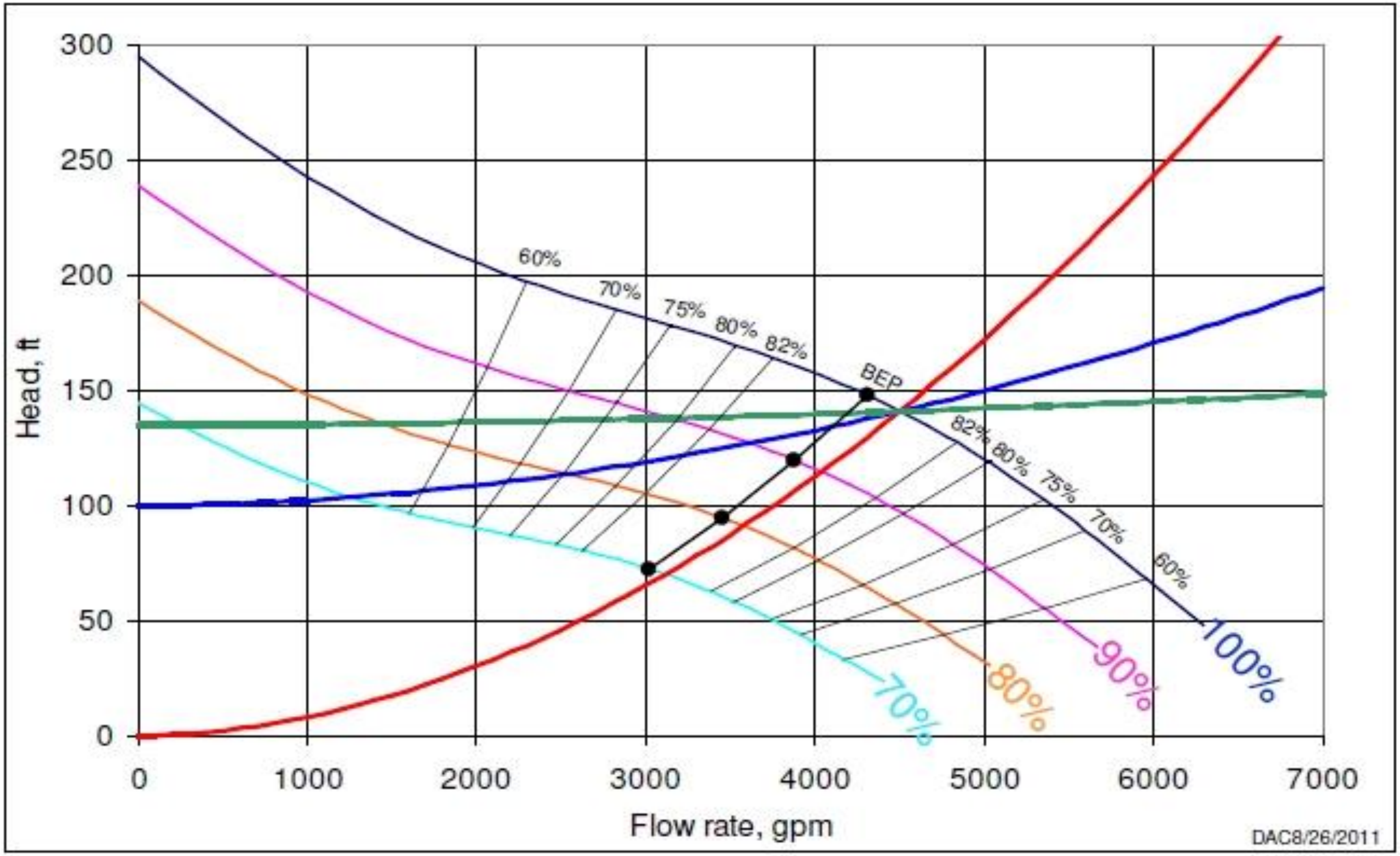
The steeper head-capacity curve for pump 3 makes for improved turndown and controllability



All three system curves with P2, variable speed

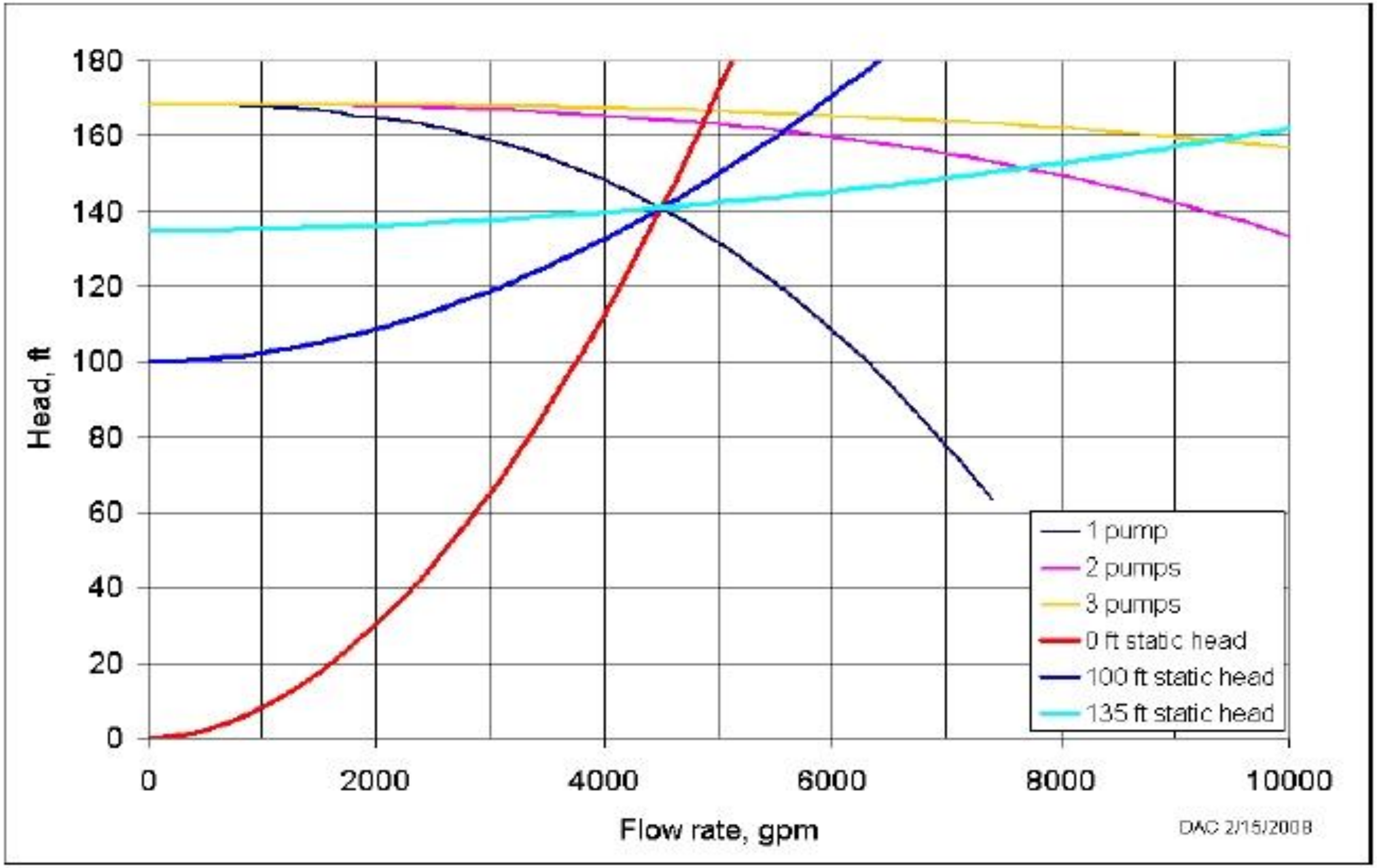


All three system curves with P3, variable speed

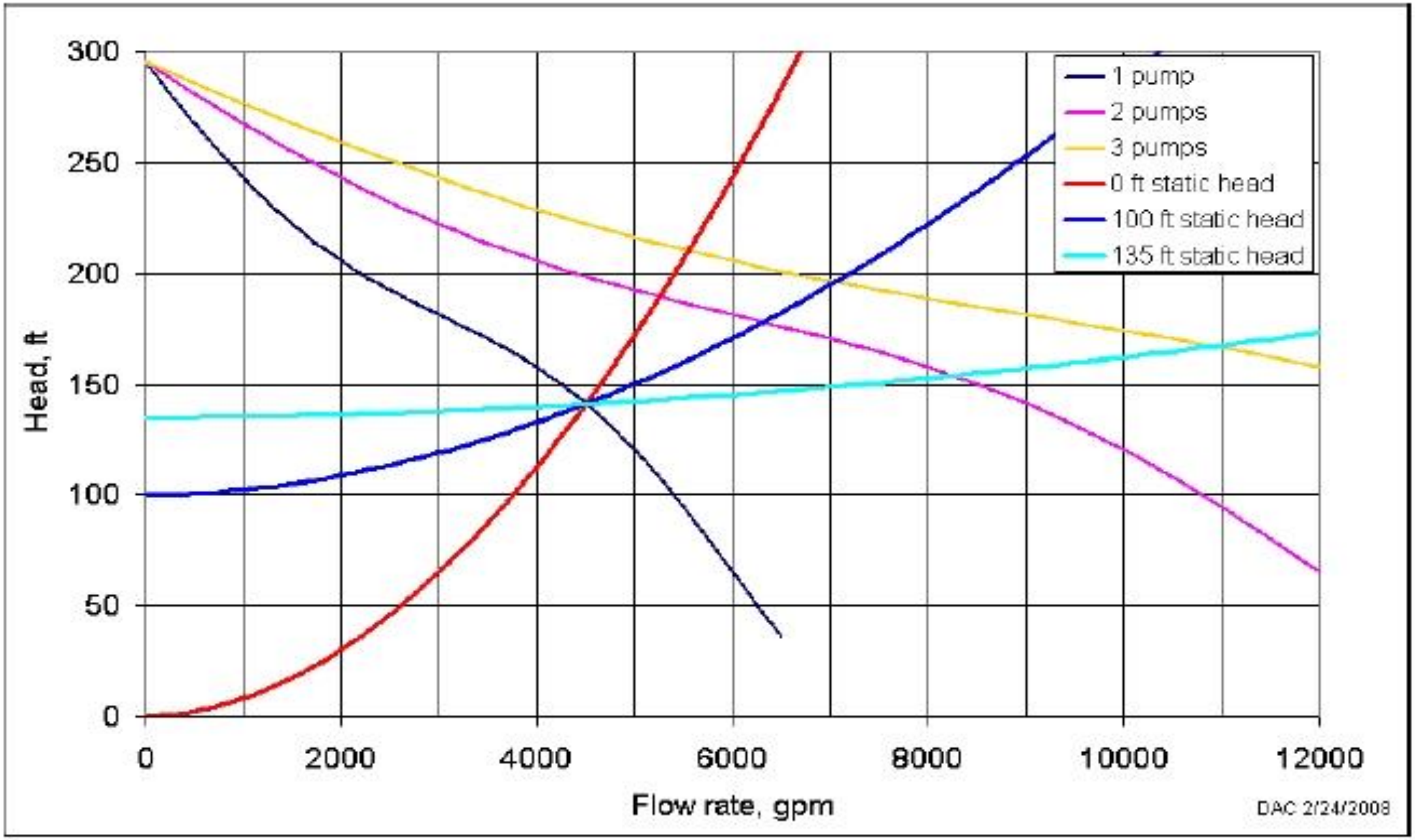


How about parallel pump operation with different system types?

Parallel pump response also depends on the nature of the system and pump curves (P2)



Parallel pump response also depends on the nature of the system and pump curves (P3)

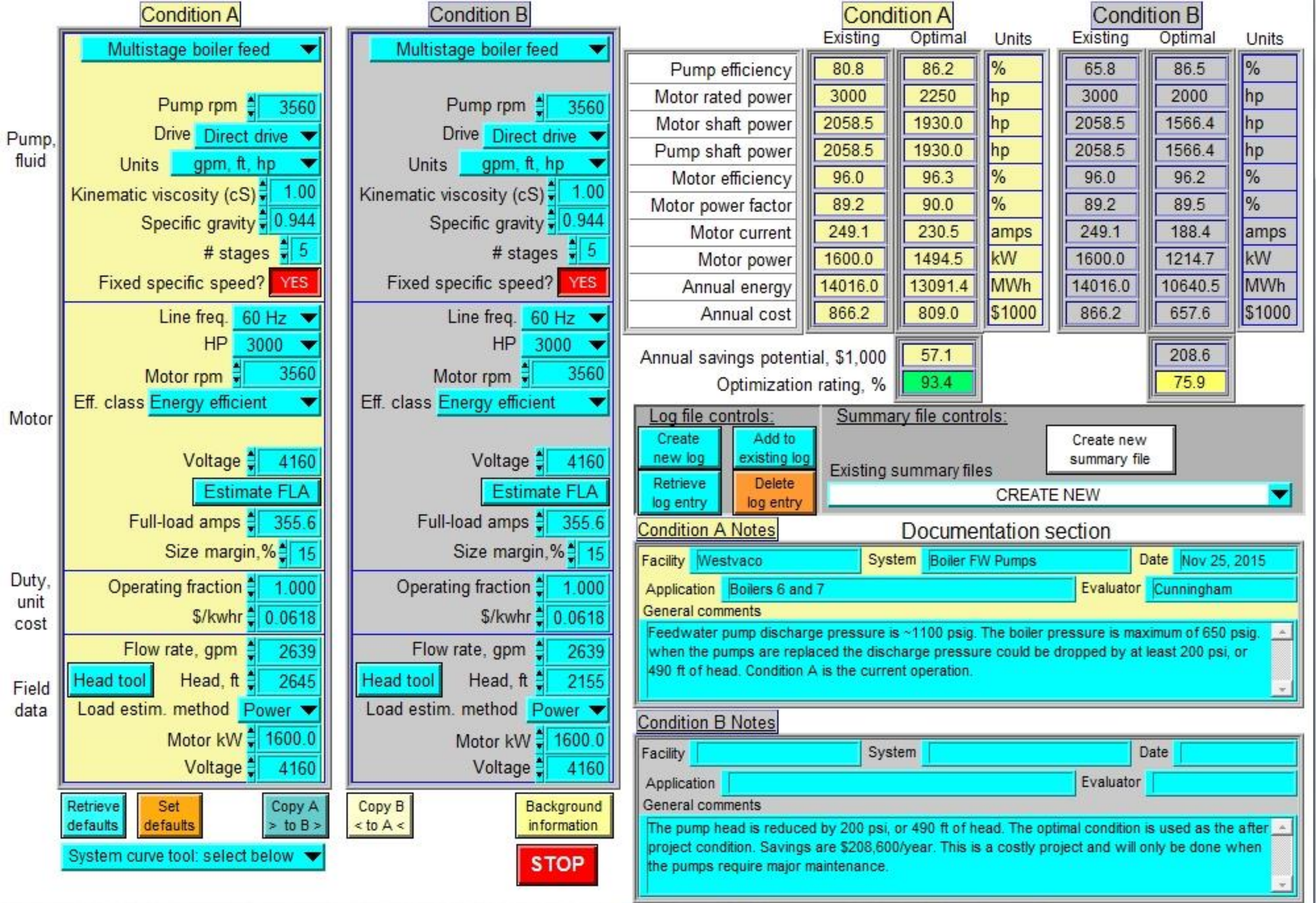


An introduction to the Pumping System Assessment Tool (PSAT)

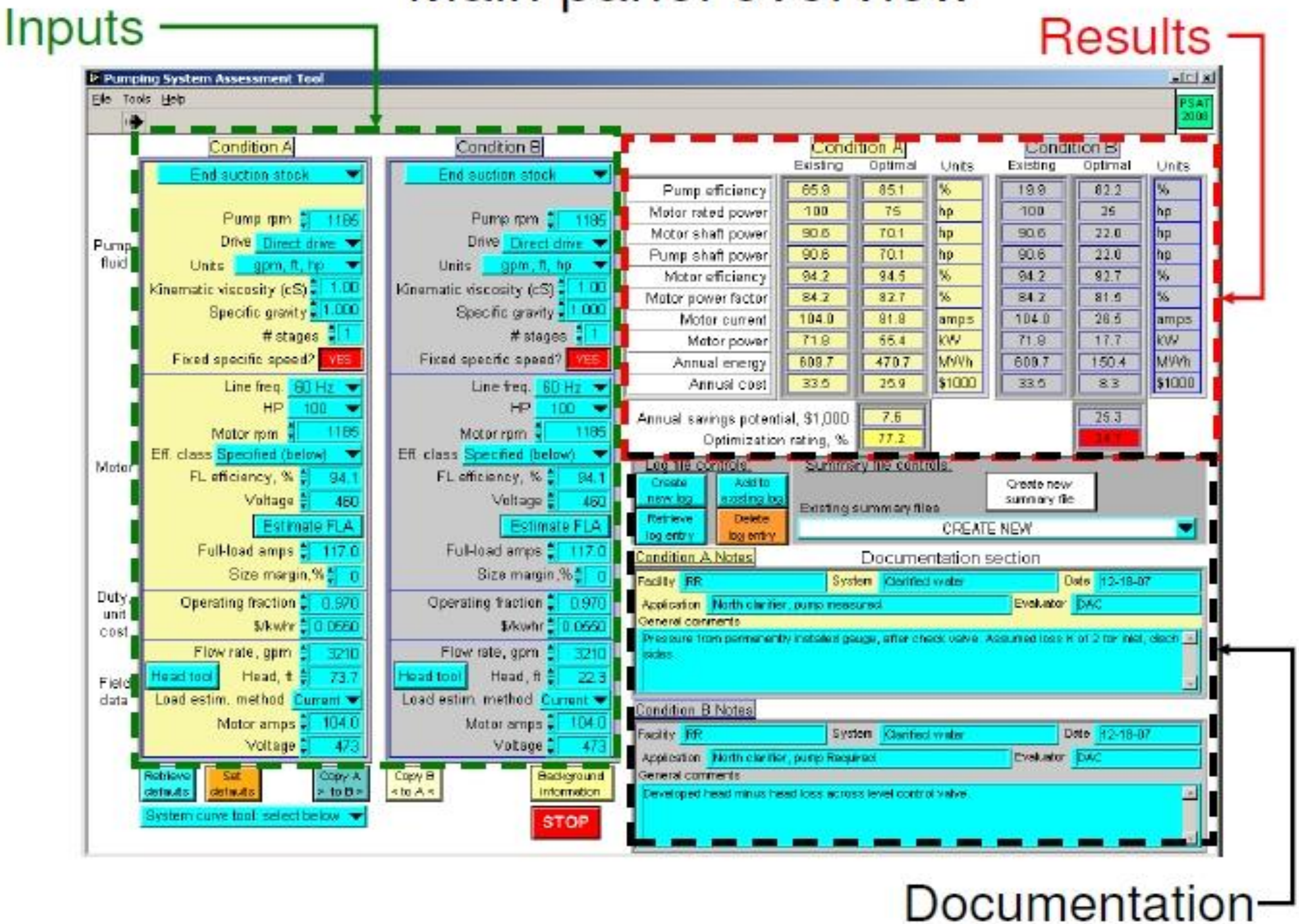
- Goal: to assist pump users in identifying pumping systems that are the most likely candidates for energy and cost savings
- Requires field measurements or estimates of flow rate, pressure, and motor power or current
- Uses pump and motor performance data from Hydraulic Institute standard ANSI/HI-1.3 and MotorMaster+ to estimate existing, achievable performance

Assessing the magnitude of the opportunity

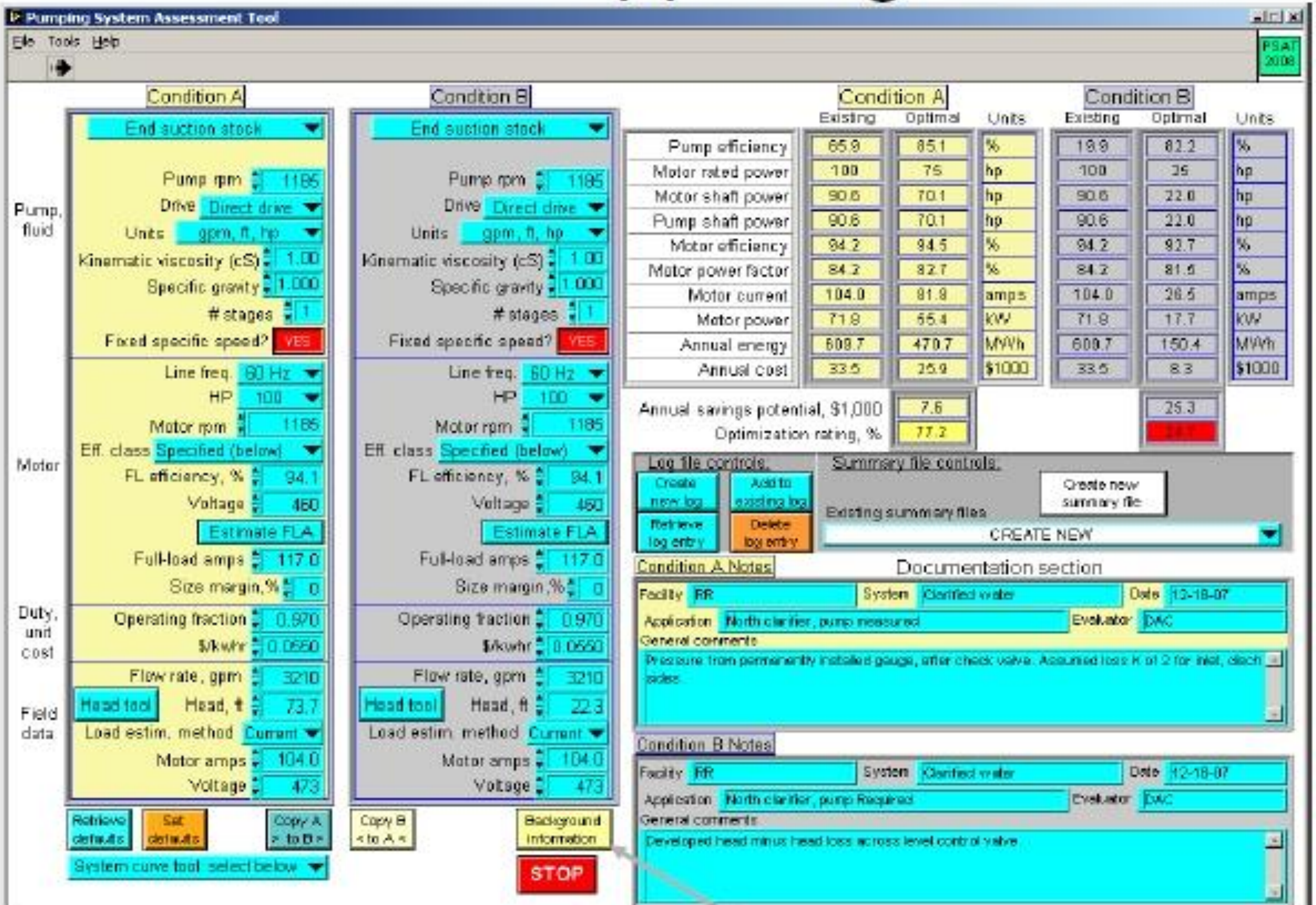
- Pumping System Assessment Tool
  - Focus on systems flagged by the size and symptom filters (size alone is, however, sufficient)
  - Quantifies energy and cost savings *opportunity*
  - Does *not* identify the *solution*


Condition A
Condition B
Multistage boiler feed
Multistage boiler feed
Pump, fluid
Pump rpm 3560
Drive Direct drive
Units gpm, ft, hp
Kinematic viscosity (cS) 1.00
Specific gravity 0.944
stages 5
Fixed specific speed? YES
Motor
Line freq. 60 Hz
HP 3000
Motor rpm 3560
Eff. class Energy efficient
Voltage 4160
Estimate FLA
Full-load amps 355.6
Size margin,% 15
Duty, unit cost
Operating fraction 1.000
$/kwhr 0.0618
Field data
Flow rate, gpm 2639
Head tool
Head, ft 2645
Head, ft 2155
Load estim. method Power
Motor kW 1600.0
Voltage 4160
Retrieve defaults
Set defaults
Copy A > to B >
Copy B < to A <
Background information
System curve tool: select below
STOP
Condition A
Existing
Optimal
Units
Condition B
Existing
Optimal
Units
Pump efficiency 80.8 86.2 % 65.8 86.5 %
Motor rated power 3000 2250 hp 3000 2000 hp
Motor shaft power 2058.5 1930.0 hp 2058.5 1566.4 hp
Pump shaft power 2058.5 1930.0 hp 2058.5 1566.4 hp
Motor efficiency 96.0 96.3 % 96.0 96.2 %
Motor power factor 89.2 90.0 % 89.2 89.5 %
Motor current 249.1 230.5 amps 249.1 188.4 amps
Motor power 1600.0 1494.5 kW 1600.0 1214.7 kW
Annual energy 14016.0 13091.4 MWh 14016.0 10640.5 MWh
Annual cost 866.2 809.0 $1000 866.2 657.6 $1000
Annual savings potential, $1,000 57.1 208.6
Optimization rating, % 93.4 75.9
Log file controls:
Create new log
Add to existing log
Retrieve log entry
Delete log entry
Summary file controls:
Create new summary file
Existing summary files
CREATE NEW
Condition A Notes
Documentation section
Facility Westvaco
System Boiler FW Pumps
Date Nov 25, 2015
Application Boilers 6 and 7
Evaluator Cunningham
General comments
Feedwater pump discharge pressure is ~1100 psig. The boiler pressure is maximum of 650 psig. when the pumps are replaced the discharge pressure could be dropped by at least 200 psi, or 490 ft of head. Condition A is the current operation.
Condition B Notes
Facility
System
Date
Application
Evaluator
General comments
The pump head is reduced by 200 psi, or 490 ft of head. The optimal condition is used as the after project condition. Savings are $208,600/year. This is a costly project and will only be done when the pumps require major maintenance.

Main panel overview



Accessing background information and supporting data



Background information

Click on Background information button to bring up a Selection menu list

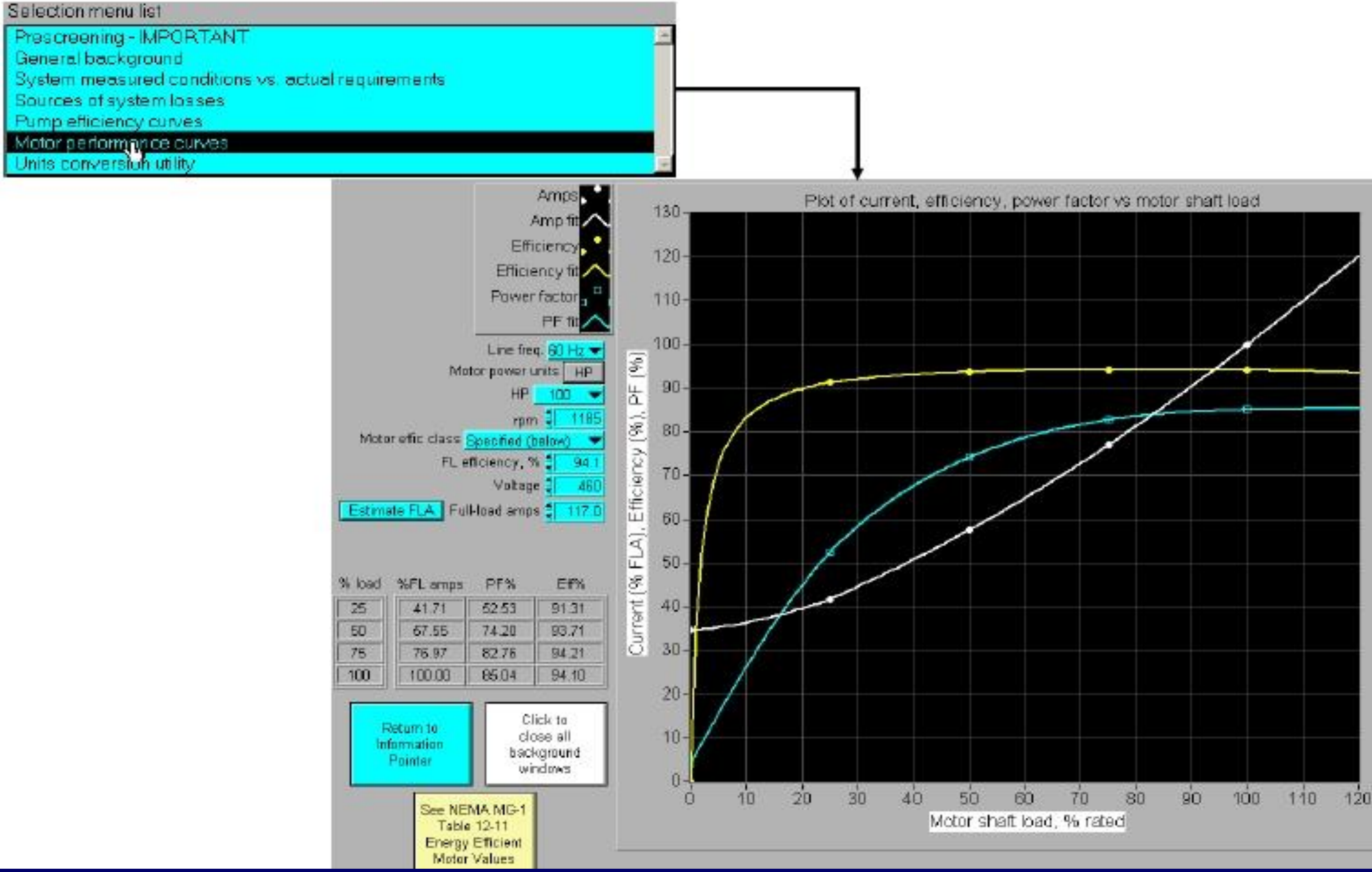
Background information

Selection menu list

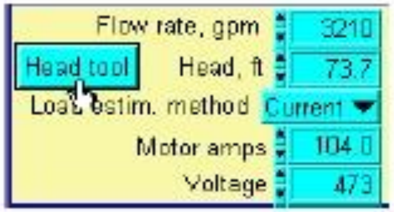
- Prescreening - IMPORTANT
- General background
- System measured conditions vs. actual requirements
- Sources of system losses
- Pump efficiency curves
- Motor performance curves
- Units conversion utility

We'll look at these items

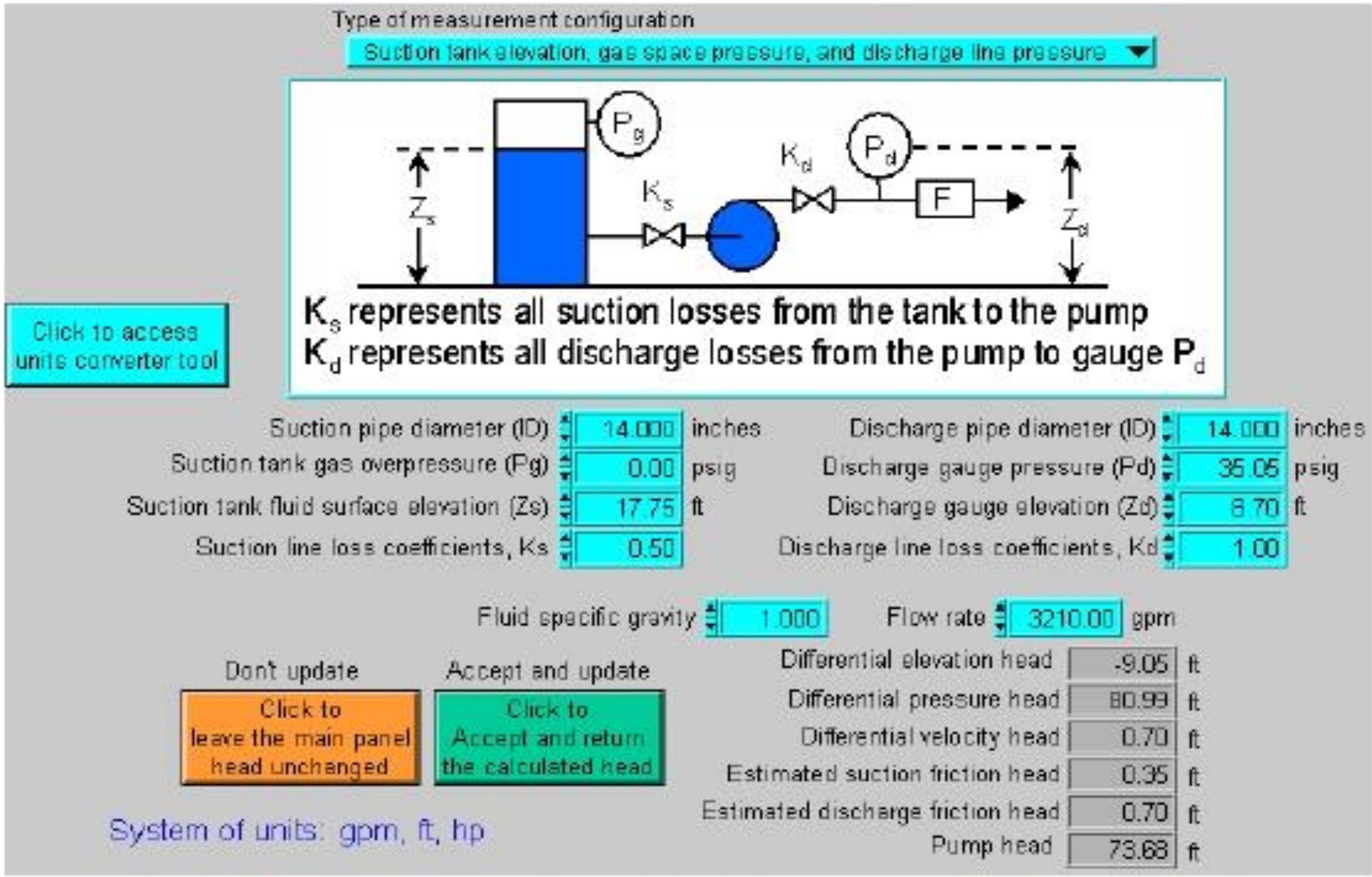
Motor performance curves access



Accessing pump head calculator



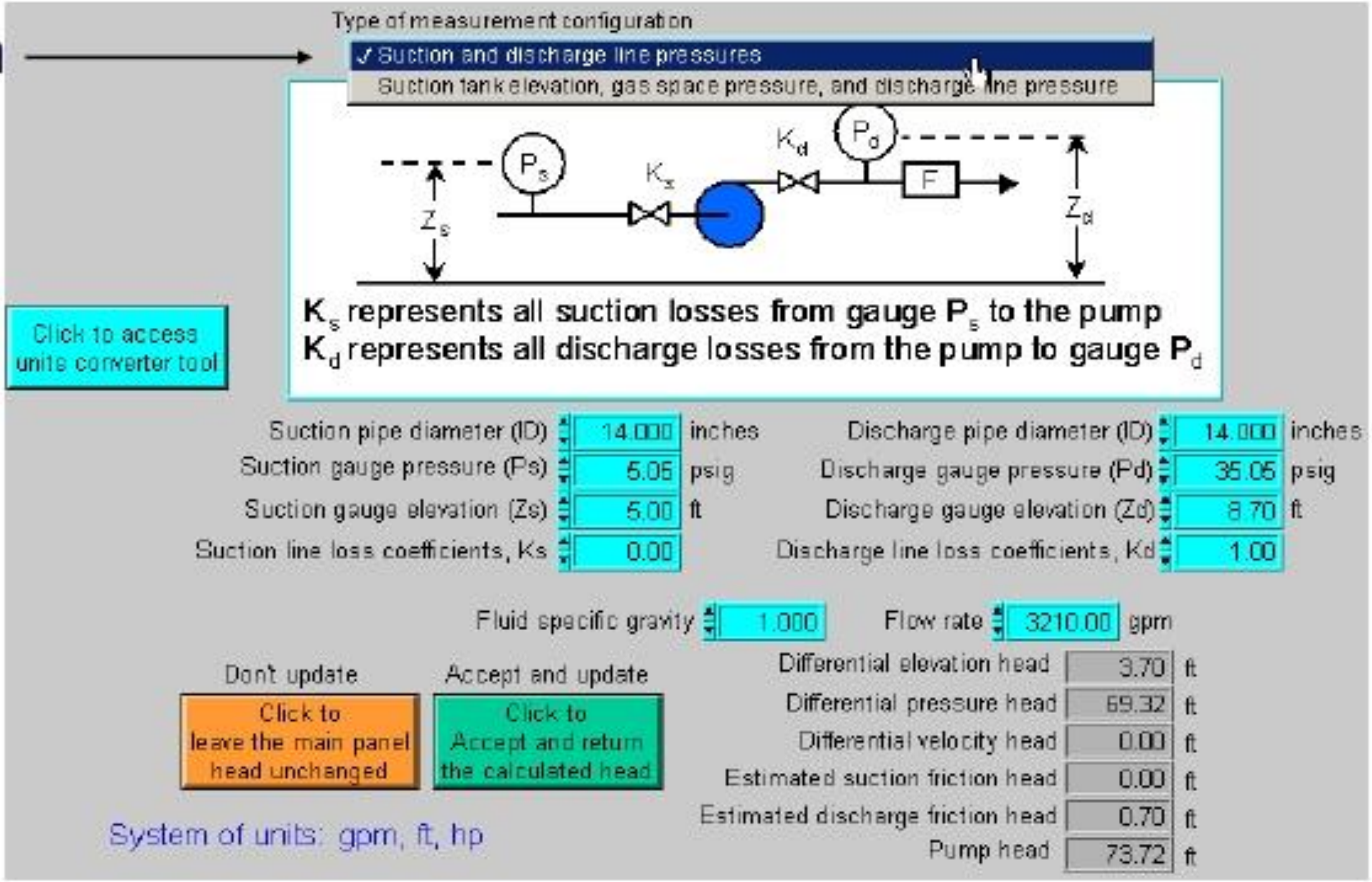
Click "Head tool" button in input for Condition A



Pump head calculation using suction source elevation and discharge pressure data

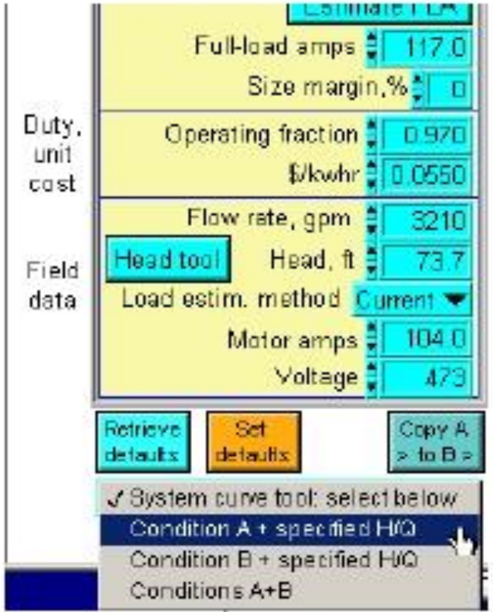
Alternate pump head calculation

Popup selection

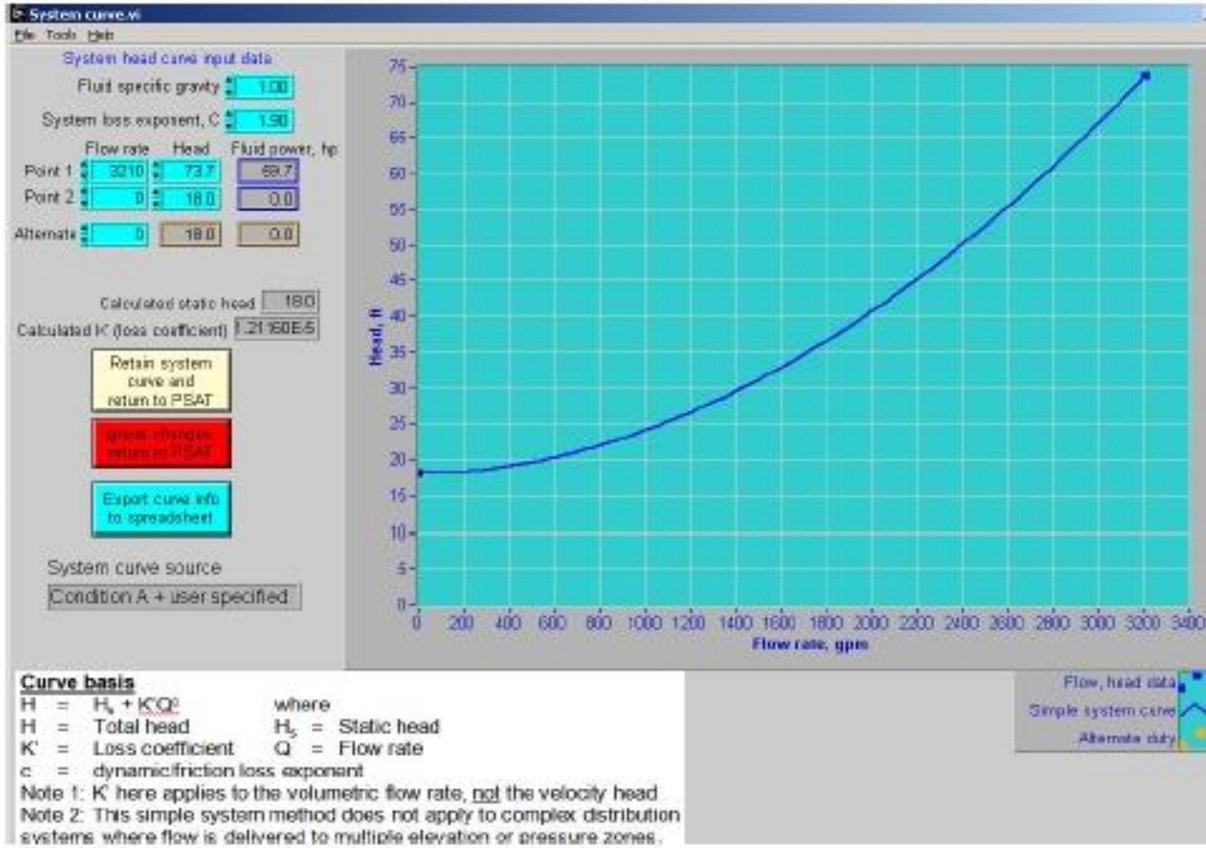


Alternate pump head calculation using suction and discharge pressure data

Accessing system curve calculator



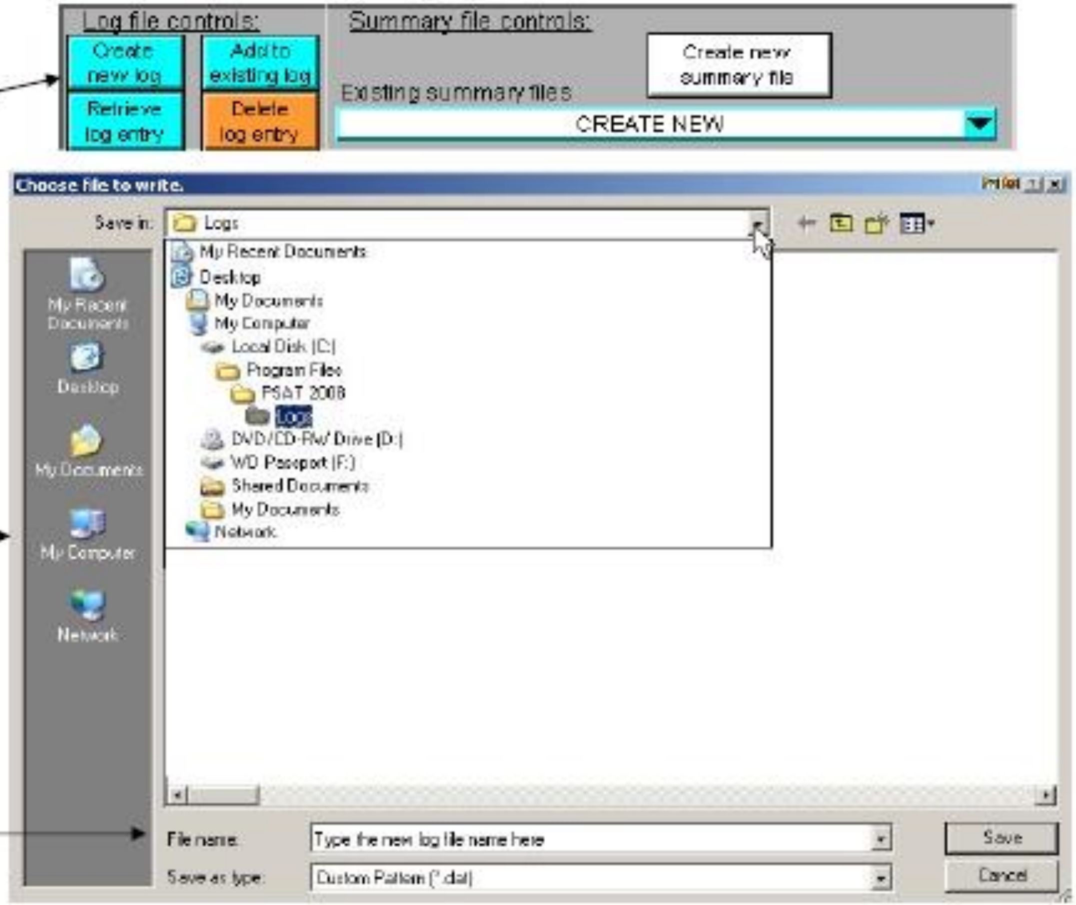
Select the desired System curve source(s)



If the system curve is retained and the analysis is subsequently logged, the system curve will be stored with the log (and available for recall).

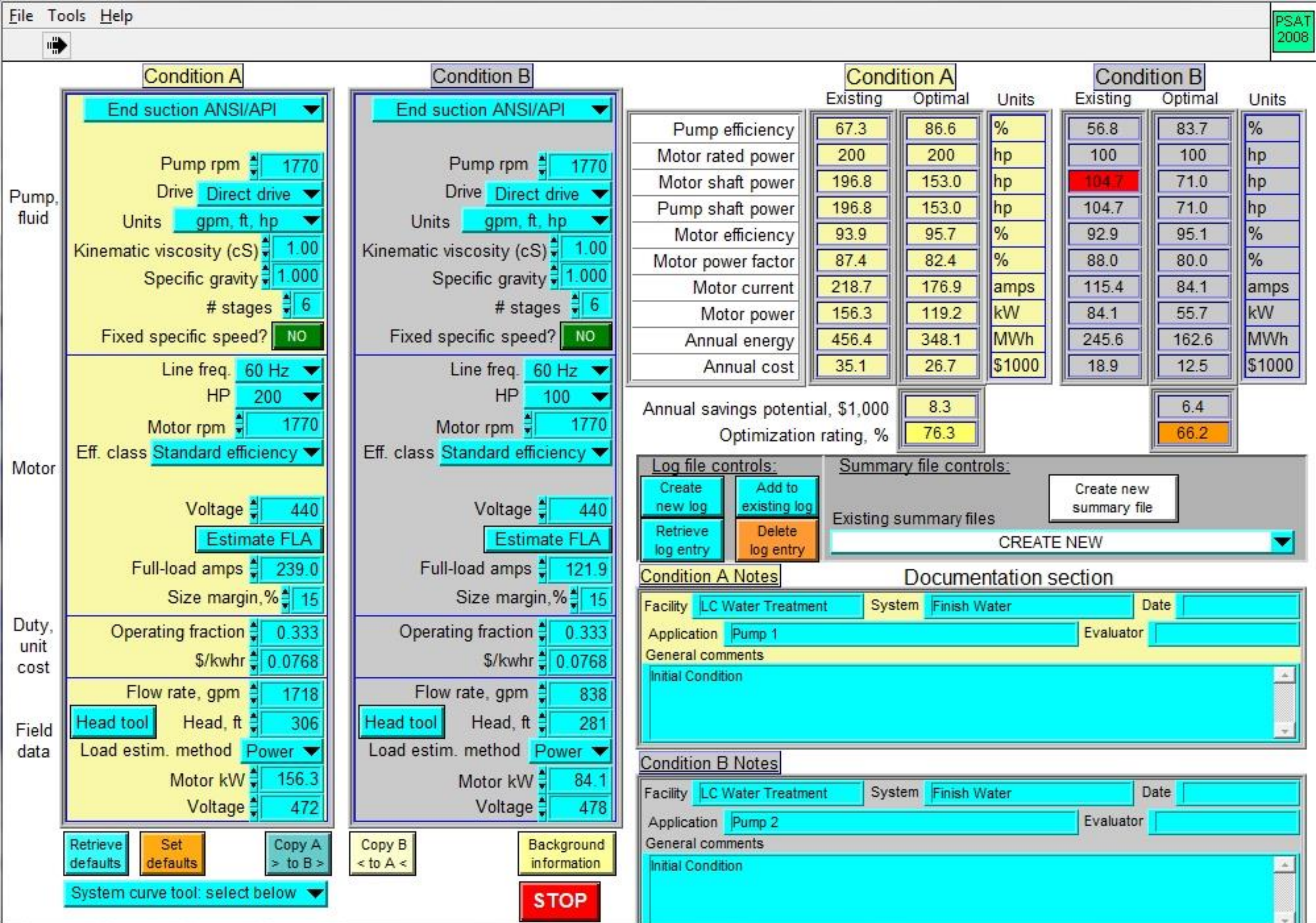
Analyses can be logged, retrieved, or deleted

Click here to create new log



The default log location is in the Logs folder, located inside the PSAT2008 folder (which is, by default, in your Program Files folder), but logs can be saved to and retrieved from other locations.

After navigating to the desired location, type the name of the log you want to create in the File name: box and click Save


File Tools Help
PSAT 2008
Condition A
End suction ANSI/API
Pump rpm 1770
Drive Direct drive
Units gpm, ft, hp
Kinematic viscosity (cS) 1.00
Specific gravity 1.000
stages 6
Fixed specific speed? NO
Line freq. 60 Hz
HP 200
Motor rpm 1770
Eff. class Standard efficiency
Voltage 440
Estimate FLA
Full-load amps 239.0
Size margin,% 15
Operating fraction 0.333
$/kwhr 0.0768
Flow rate, gpm 1718
Head tool
Head, ft 306
Load estim. method Power
Motor kW 156.3
Voltage 472
Condition B
End suction ANSI/API
Pump rpm 1770
Drive Direct drive
Units gpm, ft, hp
Kinematic viscosity (cS) 1.00
Specific gravity 1.000
stages 6
Fixed specific speed? NO
Line freq. 60 Hz
HP 100
Motor rpm 1770
Eff. class Standard efficiency
Voltage 440
Estimate FLA
Full-load amps 121.9
Size margin,% 15
Operating fraction 0.333
$/kwhr 0.0768
Flow rate, gpm 838
Head tool
Head, ft 281
Load estim. method Power
Motor kW 84.1
Voltage 478
Pump, fluid
Motor
Duty, unit cost
Field data
Retrieve defaults
Set defaults
Copy A > to B >
Copy B < to A <
Background information
System curve tool: select below
STOP
Condition A Existing Optimal Units
Condition B Existing Optimal Units
Pump efficiency 67.3 86.6 % 56.8 83.7 %
Motor rated power 200 200 hp 100 100 hp
Motor shaft power 196.8 153.0 hp 104.7 71.0 hp
Pump shaft power 196.8 153.0 hp 104.7 71.0 hp
Motor efficiency 93.9 95.7 % 92.9 95.1 %
Motor power factor 87.4 82.4 % 88.0 80.0 %
Motor current 218.7 176.9 amps 115.4 84.1 amps
Motor power 156.3 119.2 kW 84.1 55.7 kW
Annual energy 456.4 348.1 MWh 245.6 162.6 MWh
Annual cost 35.1 26.7 $1000 18.9 12.5 $1000
Annual savings potential, $1,000 8.3 6.4
Optimization rating, % 76.3 66.2
Log file controls:
Create new log
Add to existing log
Retrieve log entry
Delete log entry
Summary file controls:
Create new summary file
Existing summary files
CREATE NEW
Condition A Notes
Documentation section
Facility LC Water Treatment System Finish Water Date
Application Pump 1 Evaluator
General comments
Initial Condition
Condition B Notes
Facility LC Water Treatment System Finish Water Date
Application Pump 2 Evaluator
General comments
Initial Condition

File Tools Help

PSAT 2008

	Condition A	Condition B
Pump, fluid	End suction ANSI/API	End suction ANSI/API
Pump rpm	1770	1770
Drive	Direct drive	Direct drive
Units	gpm, ft, hp	gpm, ft, hp
Kinematic viscosity (cS)	1.00	1.00
Specific gravity	1.000	1.000
# stages	6	4
Fixed specific speed?	NO	NO
Motor Line freq.	60 Hz	60 Hz
HP	300	200
Motor rpm	1770	1770
Eff. class	Standard efficiency	Energy efficient
Voltage	460	460
Estimate FLA		
Full-load amps	339.8	225.8
Size margin, %	15	15
Duty, unit cost Operating fraction	0.333	0.397
$/kwhr	0.0768	0.0768
Field data Flow rate, gpm	2300	2100
Head tool – Head, ft	328	311
Load estim. method	Power	Power
Motor kW	240.0	147.3
Voltage	475	460

Retrieve defaults | Set defaults | Copy A > to B > | Copy B < to A < | Background information

System curve tool: select below

STOP

	Condition A Existing	Condition A Optimal	Units	Condition B Existing	Condition B Optimal	Units
Pump efficiency	62.7	87.6	%	87.4	87.3	%
Motor rated power	300	300	hp	200	250	hp
Motor shaft power	303.9	217.5	hp	189.0	189.1	hp
Pump shaft power	303.9	217.5	hp	189.0	189.1	hp
Motor efficiency	94.5	95.8	%	95.7	95.8	%
Motor power factor	87.7	83.3	%	86.5	85.1	%
Motor current	332.6	246.9	amps	213.8	217.3	amps
Motor power	240.0	169.3	kW	147.3	147.3	kW
Annual energy	700.8	494.3	MWh	512.3	512.1	MWh
Annual cost	53.8	38.0	$1000	39.3	39.3	$1000
Annual savings potential, $1,000		15.9			0.0	
Optimization rating, %		70.5			100.0	

Log file controls: Create new log | Add to existing log | Retrieve log entry | Delete log entry

Summary file controls: Create new summary file

Existing summary files: CREATE NEW

Documentation section

Condition A Notes

Facility: LC Water Treatment — System: Finish Water — Date:

Application: Pump 1 and Pump 2 together — Evaluator:

General comments: Initial Condition

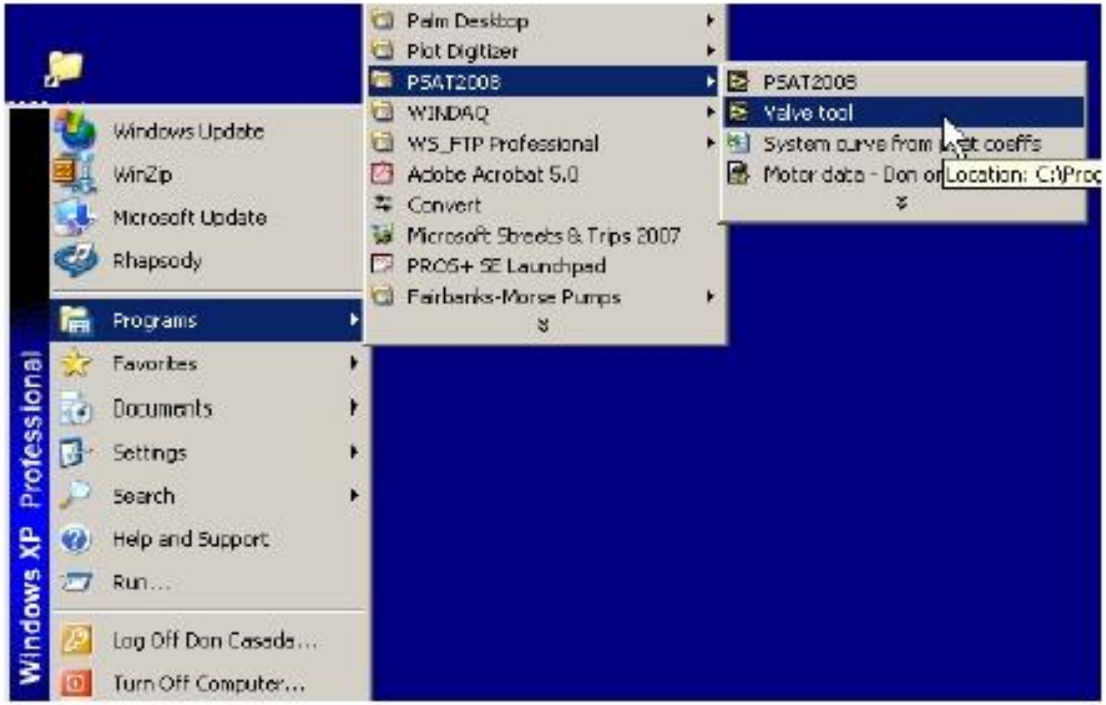
Condition B Notes

Facility: LC Water Treatment — System: Finish Water — Date:

Application: Optimization — Evaluator:

General comments: This assumes a daily production of 1.2 million gallons, at which requires 2,100 gpm for 9.52 hours/day. The "Measured power" value was adjusted to give an optimization rating of 100 simply to clarify that this is what would be expected from an optimal pump.

A valve tool is included in the PSAT2008 package



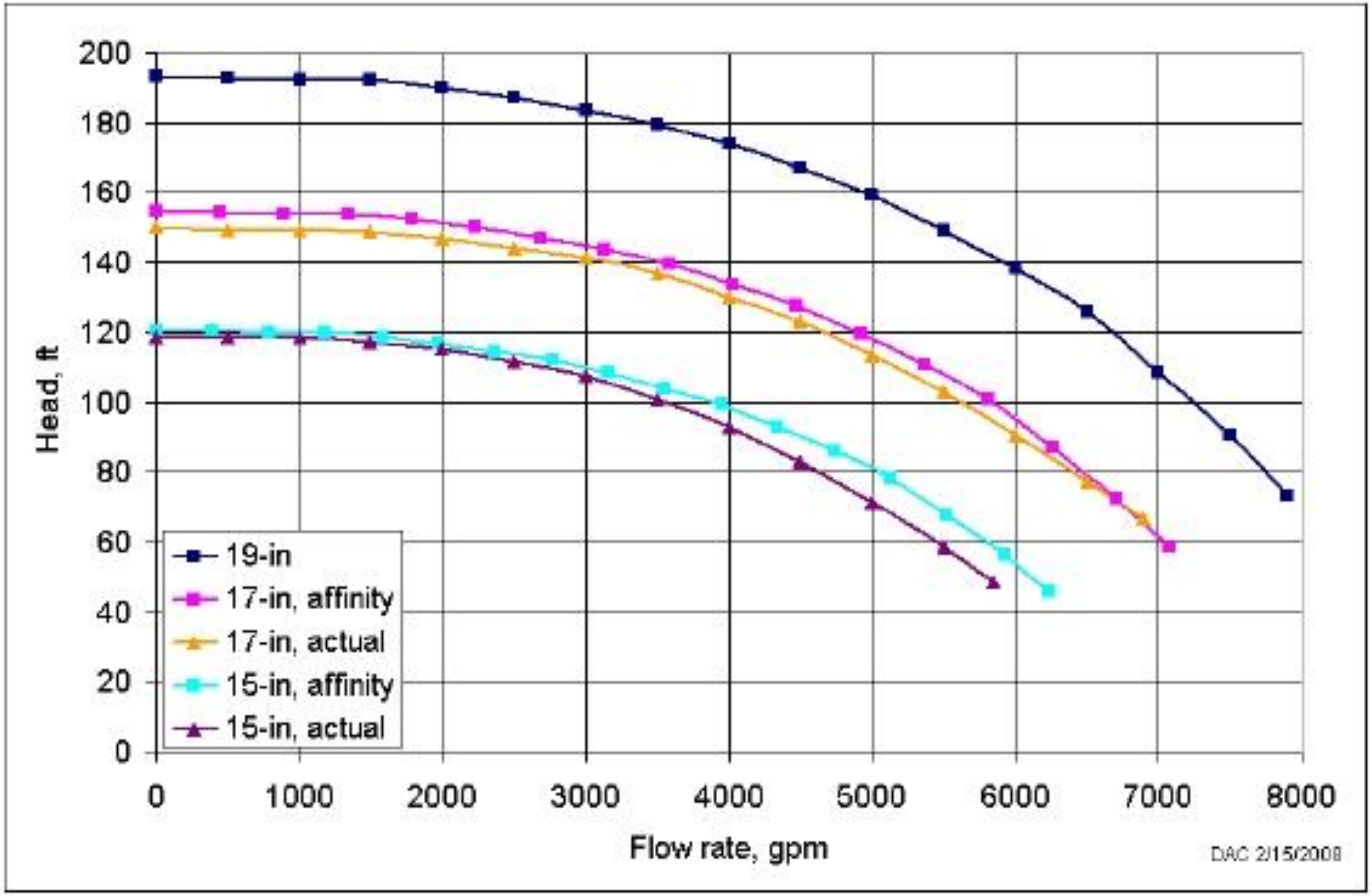
Pump affinity laws and parallel or series pump operation

Pump affinity laws can be used to predict pump curves for different speeds and impeller diameters

Speed	Diameter
$\left(\dfrac{Q_1}{Q_2}\right) = \left(\dfrac{N_1}{N_2}\right)^1$	$\left(\dfrac{Q_1}{Q_2}\right) = \left(\dfrac{D_1}{D_2}\right)^1$
$\left(\dfrac{H_1}{H_2}\right) = \left(\dfrac{N_1}{N_2}\right)^2$	$\left(\dfrac{H_1}{H_2}\right) = \left(\dfrac{D_1}{D_2}\right)^2$
$\left(\dfrac{P_1}{P_2}\right) = \left(\dfrac{N_1}{N_2}\right)^3$	$\left(\dfrac{P_1}{P_2}\right) = \left(\dfrac{D_1}{D_2}\right)^3$
$\left(\dfrac{\eta_1}{\eta_2}\right) = \left(\dfrac{N_1}{N_2}\right)^0$	$\left(\dfrac{\eta_1}{\eta_2}\right) = \left(\dfrac{D_1}{D_2}\right)^0$

Q = flow rate   H = head   P = power
N = speed   D = diameter   η = efficiency

The affinity laws aren't perfect for diameter changes: head curves



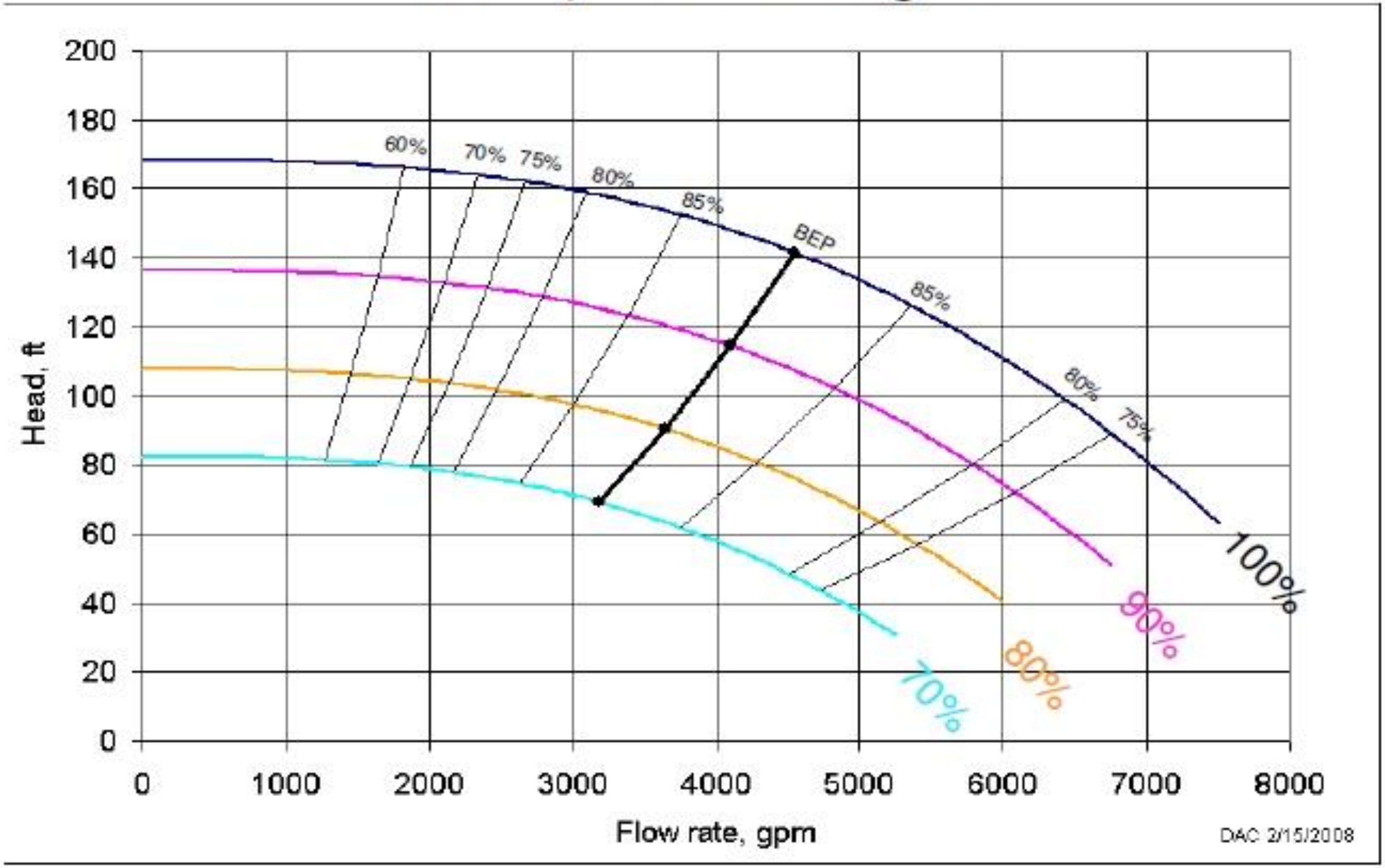
Considering a trim in impeller diameter?

Recommendations:

1. Get actual performance curves from the manufacturer, especially if the trim change being considered is large
2. Do a field performance test of the existing pump

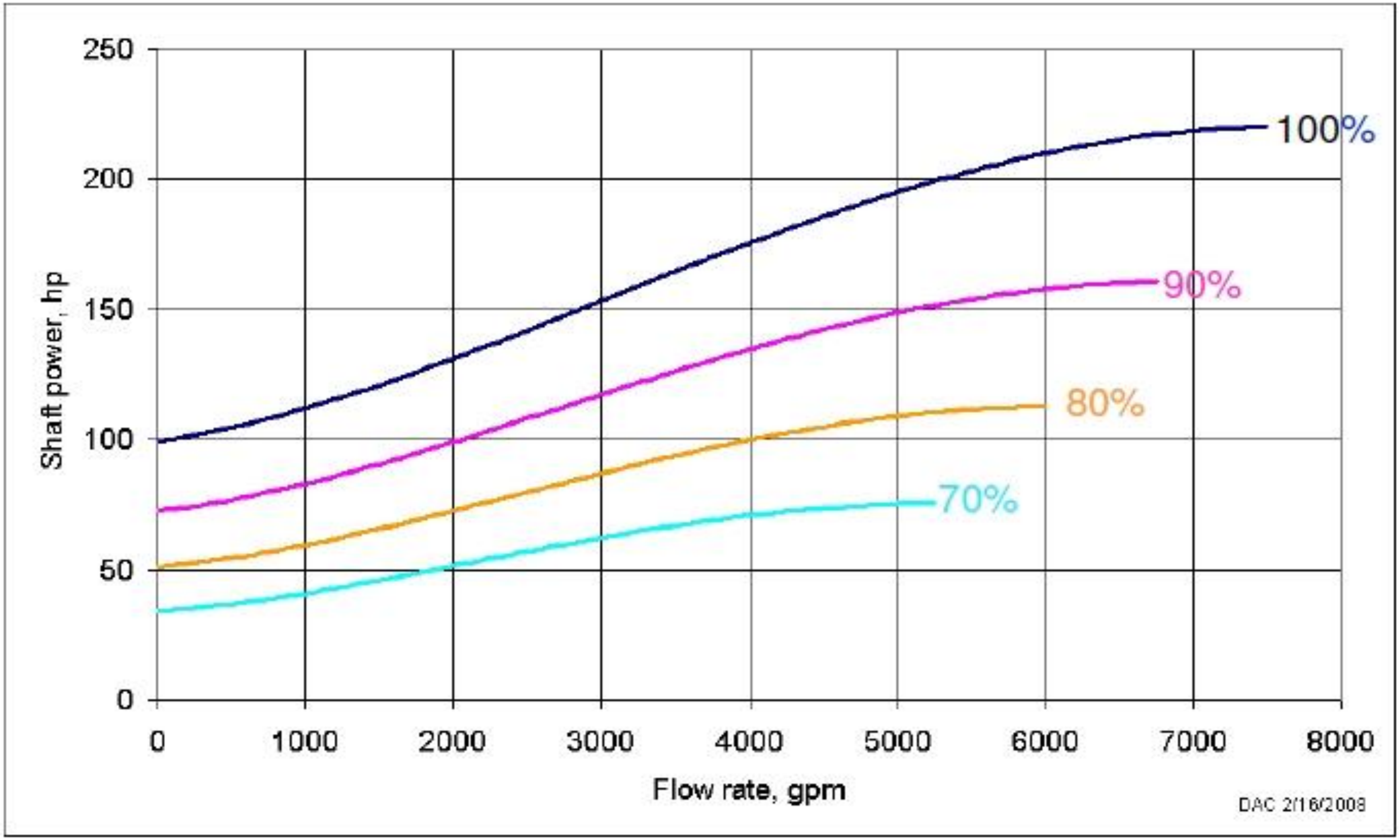
"If it is necessary to dismantle a pump after the performance test for the sole purpose of changing rotation or machining impellers to meet the tolerances, no re-test shall be required unless the reduction in diameter exceeds 5% of the original diameter." (HI-1.6, Centrifugal Pump Tests)

But the affinity laws generally hold up very well with speed changes



Note: same pump as previous slides, impeller size = 17.9 inches

Shaft power curves at four speeds



Efficiency curves at four speeds